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16. Abstract

In recent years, there has been an increasing interest in investigating the air quality benefits of traffic management strategies in light of challenges associated with the global warming and climate change. However, there has been a lack of systematic effort to study the impact of a specific traffic management strategy on mobile source Greenhouse Gas (GHG) emissions. This research is intended to evaluate mobile source GHG emissions for traffic management strategies, in which a Portable Emission Measurement System (PEMS) is used to collect the vehicle's real-world emission and activity data, and a Vehicle Specific Power (VSP) based modeling approach is used as the basis for emission estimation. Three traffic management strategies are selected in this research, including High Occupancy Vehicle (HOV) lane, traffic signal coordination plan, and Electronic Toll Collection (ETC). In the HOV lane scenario, CO_2 emission factors produced by the testing vehicle using HOV lane and the corresponding mixed flow lane are compared. In the evaluation of traffic signal coordination, total CO_2 emissions produced under the existing coordinated signal timing and the emulated non-coordinated signal timing along the same designed testing route are compared. In the study about ETC, total CO_2 emissions produced by the testing vehicle around an ETC station and a Manual Toll Collection (MTC) station located on the same toll road segment are estimated and compared. The results demonstrated that HOV lane, well-coordinated signal timing, and ETC are all effective measures to reduce mobile source GHG emissions, although the level of effectiveness is shown to be different for different strategies.

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Evaluation of Mobile Source Greenhouse Gas Emissions for Assessment of Traffic Management Strategies

by

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Report SWUTC/11/161142-1

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ABSTRACT

In recent years, there has been an increasing interest in investigating the air quality benefits of traffic management strategies in light of challenges associated with the global warming and climate change. However, there has been a lack of systematic effort to study the impact of a specific traffic management strategy on mobile source Greenhouse Gas (GHG) emissions. This research is intended to evaluate mobile source GHG emissions for traffic management strategies, in which a Portable Emission Measurement System (PEMS) is used to collect the vehicle's real-world emission and activity data, and a Vehicle Specific Power (VSP) based modeling approach is used as the basis for emission estimation. Three traffic management strategies are selected in this research, including High Occupancy Vehicle (HOV) lane, traffic signal coordination plan, and Electronic Toll Collection (ETC). In the HOV lane scenario, CO_2 emission factors produced by the testing vehicle using HOV lane and the corresponding mixed flow lane are compared. In the evaluation of traffic signal coordination, total CO_2 emissions produced under the existing coordinated signal timing and the emulated non-coordinated signal timing along the same designed testing route are compared. In the study about ETC, total CO_2 emissions produced by the testing vehicle around an ETC station and a Manual Toll Collection (MTC) station located on the same toll road segment are estimated and compared. The results demonstrated that HOV lane, well-coordinated signal timing, and ETC are all effective measures to reduce mobile source GHG emissions, although the level of effectiveness is shown to be different for different strategies.

EXECUTIVE SUMMARY

Issues regarding Greenhouse Gas (GHG) emissions have attracted world-wide attention. In the transportation sector, emissions from on-road vehicles are known as a major source of GHG emissions. As we know, the implementation of different traffic management strategies will result in changes in emission levels for different emission species, therefore, these strategies can potentially be very effective approaches to reduce mobile source GHG emissions, especially a vehicle's CO_2 emissions. However, due to real-world data constraints and limitations associated with current mobile source emission models, there has been a lack of systematic effort to study the impact of a specific traffic management strategy on mobile source GHG emission control. In this context, the primary objectives of this research are to: (1) develop an emission estimation methodology to quantify a vehicle's CO_2 emissions in a real-world traffic network; (2) design field testing scenarios to collect a vehicle's real-world emission and operational data with versus without the implementation of the selected traffic management strategies; and (3) provide a quantitative evaluation of the selected traffic management strategies in terms of their effectiveness on reducing a vehicle's CO_2 emissions.

In this research, the evaluation of traffic management strategies is fulfilled by a combined use of the field data collected by a Portable Emission Measurement System (PEMS) and a vehicle specific power (VSP) based modeling approach. The general methodology includes comprehensive data collection, the application of state-of-the-art vehicle emission modeling approach, and a thorough evaluation of the selected traffic management strategies.

Two parts of real-world data are needed to perform the proposed evaluation study. One part includes the data collected for the purpose of developing the modeling approach that meets specific needs of the emission calculation in this study; and the other part includes the data collected in the designed testing areas to facilitate the case-specific traffic management assessment. A VSP-based emission modeling approach is developed to quantify a vehicle's CO_2 emissions during its regular operations. The basic methodology for this modeling approach is binning second-by-second VSP data and computing the average emission rate in each bin. With

this partition, the average emission rate of a particular type of pollutant in that bin for a specific vehicle can be calculated. The evaluation approach is based on the comparison of emissions produced with versus without the implementation of a specific traffic management strategy. Since this research focuses on existing traffic management strategies, the testing vehicle's real-world emissions and operational data can be directly collected using the PEMS equipment. In the meantime, case-specific data collection plans need to be developed so that the vehicle's emissions under the scenario without the implementation of the selected traffic management strategy can be calculated in the real-world setting. The VSP-based emission modeling approach makes it possible to perform emission calculations by needing only the vehicle's speed and acceleration, therefore, in this study, a vehicle equipped with a GPS device is used to run with the vehicle equipped with the PEMS unit in a synchronized way under different scenarios. In this way, a pair of paralleled datasets can be obtained for the purpose of comparison.

The following conclusions are drawn from this research:

First, PEMS represents an advanced emission data collection technology. Its ability of collecting a vehicle's second-by-second emission and activity data during its regular operations provides significant advantages over all the traditional emission measurement methods. It can be applied

not only in transportation related air quality modeling and analysis, but also in the assessment of traffic management strategies.

Second, the proposed emission estimation methodology is a combination of the advantages of field testing approach and the latest modeling approach. The experimental design of the field testing scenarios provides a pilot study on the impact of a specific traffic management strategy on mobile source GHG emissions using data collected in the real-world traffic network. The VSP-based emission modeling approach provides a credible basis for emission estimation. The validation results indicate that the accuracy rate of the proposed modeling approach is about 90%.

Third, HOV lane, well-coordinated signal timing, and ETC are all effective measures to reduce mobile source GHG emissions; however, the level of effectiveness is different for different strategies.

Fourth, the results from HOV lane analysis illustrate that the testing vehicle produces less mass CO_2 emissions per mile by using HOV lane during peak periods. Without the consideration of the effect of HOV lane on vehicle miles traveled, the emission reduction rate on the first testing day is 3.56 percent, and due to an increased traffic demand on the corresponding MF lane on the second testing day, the emission reduction rate by using HOV lane increased to 10.42 percent.

Fifth, based on the comparison of CO_2 emissions generated by the testing vehicle under the existing coordinated signal timing and those generated under the emulated non-coordinated signal timing, it is found that the non-coordinated signal timing designed in this study leads to about 56 percent increase in CO_2 emissions. It is also found that the increase of traffic flow may compromise the effectiveness of signal coordination in terms of their influence on mobile source GHG emission control.

Finally, the results from the ETC analysis shows that the total CO_2 emissions produced by the vehicle around the ETC station are only 30 percent of those produced around the corresponding MTC station; therefore, ETC is a very effective traffic management strategy for reducing mobile source GHG emissions.

In order to fulfill a more comprehensive analysis about the relationship between traffic management strategies and mobile source GHG emissions, the following recommendations are made for future study:

1. Improve the VSP-based emission modeling approach by increasing the size of the database used for the model development and develop a finer VSP binning method.

2. Evaluate the impact of traffic management strategies on mobile source GHG emissions with the use of different vehicle types.

3. Incorporate cost-benefit analysis into the evaluation of traffic management strategies, such as construction cost, operation and maintenance cost, and comprehensive air quality benefits.

4. Evaluate the impact of traffic management strategies on regional mobile source GHG emission reduction.

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CHAPTER 1: INTRODUCTION

Climate change is one of the most serious worldwide environmental problems. Most scientists agree that the major cause of climate change is greenhouse gases (GHGs) resulting from human activities. In the United States, transportation is a major source as well as the fastest growing sector of GHG emissions. In addition, almost all of the increases in transportation related GHG emissions since 1990 are brought about by on-road vehicles, i.e. mobile source, in the form of carbon dioxide (CO_2) (EPA, 2010a; EIA, 2008). Therefore, if we do not promptly and substantially reduce mobile source GHG emissions, adverse consequences of the global warming may only become worse in number and intensity.

It is well understood that the implementation of different traffic management strategies will result in changes in emission levels for different emission species; thus, traffic management strategies are potentially a very effective approach to reduce different types of mobile source emissions. However, due to the real-world data constraints, limitations associated with current GHG emission models, and a lack of comprehensive analysis of traffic management related GHG emission reduction methodologies, there has been a lack of systematic attempt to study the impact of a specific traffic management strategy on mobile source GHG emissions.

To address the gap that exists in the current practice, this research intends to provide a quantitative evaluation of three selected traffic management strategies in terms of their effectiveness on reducing a vehicle's CO_2 emissions with a combined use of field testing approach and modeling approach. The merit of the proposed methodology is that it not only uses the existing model as the basis for emission estimation, but also combines it with real-world tests. Using the proposed methodology, a vehicle' CO_2 emissions for scenarios with versus without the implementation of the selected traffic management strategies are estimated and compared.

1.1 Background of Research

1.1.1 Mobile Source GHG Emissions

GHGs mainly include CO_2, methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs), in which CO_2 from fossil fuel combustion has accounted for approximately 80 percent of global warming potential (GWP) weighted emission in 2007 (EPA, 2009a). In the United States, the transportation sector accounts for about 33 percent of total CO_2 emissions, giving the largest share of any end-use economic sector. Nearly 60 percent of transportation-related CO_2 emissions result from gasoline consumption for personal vehicle use. The remaining come from other transportation activities, such as the combustion of diesel fuel in heavy-duty vehicles and jet fuel in aircrafts (EPA, 2010a). Therefore, the mobile source GHG emissions discussed in this study focus on vehicles' CO_2 emissions.

Four key factors affect mobile source GHG emissions, including vehicle technology, fuel economy, vehicle miles traveled (VMT), and vehicle/system operations (FHWA, 2008). The traffic management has been implemented to reduce the growth in VMT and improve the efficiency of transpiration system operations. Related policy scenarios include congestion pricing, speed limit reduction, public transit development, etc. (Rodier, 2008). Transportation engineers and planners also look to switch to alternative fuels, use more fuel efficient vehicles, and enhance Inspection and Maintenance (I/M) program for in-using vehicles to lower mobile source GHG emissions.

The development of mobile source GHG emission inventory starts with an estimation of fuel consumption from the Energy Information Administration (EIA) of the U. S. Department of Energy. The fuel consumption statistics made by EIA are believed to be very accurate in accounting for the combined fuel consumption of all economic sectors, but great uncertainty may occur when one apportions the fuel- and sector- specific estimates to certain sources (Davis, et al., 2007). The estimation of mobile source GHG emissions at the project level is usually realized through the field-testing approach or modeling approach. Therefore, the accuracy and applicability of these approaches are greatly affected by the selected GHG emission measurement technologies or emission models.

1.1.2 Mobile Source GHG Emission Reduction Practice

Mobile source GHG emission reduction practices are conducted at different levels from federal government to local transportation agencies. U.S Environmental Protection Agency (EPA) plays a significant role in this area (EPA, 2010b). EPA's mobile source GHG emission reduction programs include Clean Energy-Environment State Partnership, Climate Leaders, Energy Star, and EPA Office of Transportation and Air Quality Voluntary Programs, such as National Clean Diesel Campaign (NCDC), SmartWay Transport Partnership, Clean School Bus USA, Best Workplaces for Commuters, and EcoCar (EPA, 2010c). Other federal mobile source GHG emissions reduction initiatives include Climate VISION Partnership, Tax Incentives to Reduce GHG Emissions, and Voluntary Greenhouse Gas Reporting Program. These programs promote voluntary GHG reduction by encouraging auto manufacturers to implement cost-effective clean energy and environmental strategies, developing comprehensive GHG emission control regulations, and providing targeted incentives to spur the use of more energy-efficient technologies.

At the state level, specific climate policies are adopted to address the problem of mobile source GHG emissions. Even though, currently, there is no federal requirement to report GHG emissions, as of November 2008, 18 states have imposed mandatory reporting of GHG emissions (EHS Today, 2009). California has passed legislation requiring the state's Air Resources Board to set GHG emission standards for new passenger cars and light-duty trucks from the model year 2009 and later. In addition, The California Zero-Emission Vehicle Incentive Program provides grants of up to $9, 000 per vehicle toward the purchase or lease of new zero-emission vehicles. The Advanced Travel Center Electrification (ATE) program is conducted in the states of Arkansas, Georgia, New York, and Tennessee, which provides energy-efficient heating, ventilation, and cooling systems (HVAC) for use by truckers at travel centers and other areas where drivers stop and idle their vehicles.

At local and project level, various practices have also been pursued to reduce mobile source GHG emissions. Such practices include improving traffic management and public transportation amenities to optimize transportation system operation; accelerating vehicle retirement to reduce transportation fuel consumption; and implementing financial incentives, pricing regulations, car sharing, and broader use of telecommunication technologies to reduce travel and congestion (Euritt et al., 1996; Greene and Schafer, 2003).

1.1.3 Mobile Source GHG Emission Estimation

Accurate quantification of vehicles' emissions is the basis for evaluating the air quality benefits of any traffic management strategies. Since 1970s, various emission measurement methods have been developed to collect vehicles' emission data during field testing, in which chassis dynamometer testing, tunnel testing, remote sensing, and Portable Emission Measurement Systems (PEMS) are the most widely used methods. Even though these technologies are mainly developed to measure hazardous pollutants from vehicle exhausts, such as hydrocarbons (HC), nitrogen oxide (NO_X), and carbon monoxide (CO), they all have the ability to quantify CO_2 emissions from on-road vehicles.

A wide range of GHG emission models have also been developed to estimate the amount of mobile source GHG emissions produced under various traffic management strategies. Direct GHG emission estimation models include MOBILE6 model, NONROAD model, National Mobile Inventory Model (NMIM), EMission FACtors Model (EMFAC), and Climate Leadership in Parks (CLIP) model (EPA, 2006a; EPA, 2006b; EPA, 2006c; CARB, 2010; NPS and EPA, 2007). These models focus on transportation sources, and are designed to develop emission factors or emission estimates for pollutants emitted during vehicles' use. Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) Model, Lifecycle Emissions Model (LEM), and Motor Vehicle Emissions Simulator (MOVES) are also capable of GHG emissions quantification. These models are termed as life-cycle models, which take into consideration not only tailpipe emissions but also pre-combustion emissions (ANL, 2009; Delucchi, 2002; EPA, 2010d).

Of all the GHG emission models examined, EPA's MOVES provides the most functionality and applicability for conducting different types of transportation GHG analysis (ICF Consulting, 2006). MOVES uses Vehicle Specific Power (VSP) to characterize emission rates for the running exhaust emission process, which combines into one single parameter numerous physical factors that are influential to vehicle fuel consumption and emissions, such as vehicle speed, acceleration, road grade, and road load parameters (Koupal et al, 2002). In addition, existing studies have found that the VSP binning approach has the most consistent performance when matching VSP distribution with real-world CO_2 emissions per unit time (EPA, 2002). Therefore, a VSP-based modeling approach is used as the basis for emission estimations in this research.

1.1.4 Issues and Research Gaps

Although a lot of research has been conducted to evaluate air quality benefits of specific traffic management strategies, such as high occupancy vehicle (HOV) lane, bus exclusive lane, traffic signal control plan, electronic toll collection (ETC), speed restriction, banning heavy duty vehicles, and adaptive cruise control, current practices still face several barriers in further integrating GHG emissions reduction in transportation planning. Particular challenges arise from real-world data constraints, limitations associated with current GHG emission models, and lack of systematic analysis of traffic management related GHG emission reduction methodologies.

Real-world data constraint is resulted from the limitation of traditional emission measurement technologies. For instance, dynamometer testing takes place in optimum ambient conditions (fixed temperature, pressure, and humidity) on a predefined driving cycle, which is unable to reflect the vehicle's emissions in real-world driving conditions; tunnel test does happen in the real-world driving settings, but the results only represent average emission factors generated in the tunnel; RES is good at giving instantaneous estimate of emission performance of a large amount of vehicles in different classes, but which cannot capture vehicles' corresponding emission rates under different driving patterns (acceleration, deceleration, and cruising) and engine temperature over an extended period of time.

Limitations associated with the existing GHG emission models are another barrier to incorporate GHG emission control into traffic management. Take EPA's MOBILE6 as an example. MOBILE6 model can perform CO_2 emission estimate, but the resulting CO_2 emission factors do not vary with the vehicle's speed or driving cycle. For this reason, MOBILE6 is inappropriate for any kind of detailed traffic management planning or project level emissions analysis, which is likely to involve changes of congestion levels and vehicle speeds (Grant et al, 2008). California's EMFAC model also estimates vehicle emissions by average trip speed. In addition, EMFAC does not include speed corrections for most vehicle classes for CO_2. This model is therefore insensitive to the impact of traffic conditions on the CO_2 emissions of vehicles in different classes (CARB, 2007).

Because there are no regulations addressing GHG emissions from transportation sources (except California), the state department of transportation (DOT), metropolitan planning organizations (MPOs), and other transportation agencies have limited experiences in analyzing the impact of traffic management strategies on mobile source GHG emissions. In addition, researchers and practitioners are concerned that the current modeling approaches that facilitate the GHG impacts assessment are insufficient for being used to conduct the types of analysis necessary to strategically address GHG emissions at project, local, and regional levels. Therefore, there is a lack of systematic analysis of traffic management related GHG emission reduction methodologies.

1.2 Objectives of Research

The research conducted in this study is motivated by the need to reduce mobile source GHG emissions from the perspectives of transportation planning and traffic management. In light of the above discussion, this research is intended to achieve three objectives:

1. Develop an emission estimation methodology to quantify a vehicle's CO_2 emissions in a real-world traffic network;

2. Design field testing scenarios to collect a vehicle's real-world emission and operational data with versus without the implementation of the selected traffic management strategies; and

3. Provide a quantitative evaluation of the selected traffic management strategies in terms of their effectiveness on reducing a vehicle's CO_2 emissions.

1.3 Outline of the Report

This report is organized into five chapters:

The first chapter provides readers with the background of mobile source GHG emissions, state-of-the-art mobile source GHG emissions reduction practices, and state-of-the-practice mobile source GHG emissions estimation. It also presents the problems identified in the current studies on the evaluation of traffic management strategies for mobile source GHG emissions, which is then followed by a description of research objectives.

The second chapter summarizes existing studies related to GHG emissions data collection methods, mobile source GHG emission models, and state-of-the-art assessment of traffic management strategies in terms of their impact on mobile source GHG emissions.

The third chapter describes the design of the study. It presents when, where, and how the CO_2 emissions produced by the testing vehicle are collected for the development of the proposed emission modeling approach and for the evaluation of the selected traffic management strategies. It introduces the methodology on how the VSP-based GHG emission modeling approach is developed with a combined use of real-world data and state-of-the-art emission modeling approach. The design of the assessment of traffic management strategies in terms of their impact on mobile source GHG emission reduction is also introduced.

The fourth chapter presents the details of the results from this research, including the establishment and validation of the proposed emission modeling approach, and a discussion about the results generated from the application of this approach. An evaluation of the selected traffic management strategies is also presented based on the resulting emission estimations.

The final chapter summarizes what has been accomplished in this study. It provides conclusions and makes recommendations for future research covered under this subject.

CHAPTER 2: LITERATURE REVIEW

As one of principle causes to the air quality problems associated with the global warming and climate change, mobile source GHG emissions have been given significant attention and the research in this area has gone through a remarkable development. In order to gain better insights into this field and conduct the research in this study in the most up-to-date setting, a comprehensive literature review is of significant importance. This chapter reviews major GHG emission measurement methods, state-of-the-art mobile source GHG emission models, and existing studies on air quality benefit assessment of traffic management strategies. Based on the review results, limitations that exist in the current research are presented and the methodology that will be used in this research is identified.

2.1 Major GHG Emission Measurement Methods

The quantification of vehicles' emissions depends on emission measurement methods. The research in this study requires the use of emission measurement technology to collect mobile source GHG emissions under different traffic management strategies. Currently, there are four major emission measurement methods: Chassis Dynamometer Test, Tunnel Test, Remote Sensing, and PEMS.

2.1.1 Chassis Dynamometer Testing

Chassis dynamometer is a standard tool for vehicle emission tests. It is designed to simulate the road load to measure exhaust emissions via predefined driving schedules in an exhaust emission laboratory (EPA, 2010e). The test system usually includes complex emissions sampling equipment and exhausts emissions analyzer, which enable the system to measure exhaust emissions based on the level of dynamics of each driving situation and specific characteristics of each vehicle, such as model, year, mileage, engine type, fuel type, emission control standards, etc. In recent years, chassis dynamometer has been improved by incorporating advanced roller type, quick reacting system, and modern responsive electrical inertia simulation system, which allow each vehicle to be tested under smoothest running, realistic loading of the tested vehicle's powertrain, and accurate simulated road conditions (Dinkel, 2000). The application of this technology has provided the majority of emission data for developing a number of in-using emission models, including EPA's MOBILE series model and MOVES model (EPA, 2004a; EPA, 2010f). However, due to the high cost of the testing equipment and long time occupation of testing vehicles, for many special applications, chassis dynamometer is not the first choice. In addition, since chassis dynamometer testing is conducted based on standard driving schedules under laboratory settings, the derived data can only be an approximation to "on-road" conditions; thus they are not able to reflect vehicles' emissions in the real-world network.

2.1.2 Tunnel Study

Wind tunnel studies were applied in vehicle emission measurement since 1980s. This method uses a pollutant diffusion model to estimate emission factors for each individual vehicle based on the fleet information, pollutant concentration, wind speed, and other environmental factors observed in the tunnel. Emission factors obtained in this method represent the overall emission level of each pollutant under real-world driving conditions in the tunnel. However, since the tunnel is a self-contained place, road conditions and driving operations in it are much less complicated than those in the real-world traffic network; therefore the emission data obtained in the tunnel is not applicable to evaluating the influence of traffic management strategies on vehicle emissions.

2.1.3 Remote Emission Sensing (RES)

Remote emission sensing was developed at the University of Denver, Colorado in 1990s. This technology uses infrared (IR) or Ultraviolet (UV) spectroscopy to identify high-emitting vehicles as they pass through the testing site. By placing an IR or UV light transmitter on one side of the road and directing its beam into a detector module on the other side, when a vehicle drives through the beam, the computer compares the difference of intensity between the emitted and the received beams to determine the percentage of HC, NOx, CO_2, and CO in the vehicle exhausts.

If the level of emission rate is above a certain threshold, a freeze-frame video system will then be employed to digitize an image of the license plate number of the offending vehicle (Virginia DOEQ, 2003; EPA, 2004b). This technology is able to accomplish an emission test at a specific location during vehicles' real-world operating conditions and generate a large amount of emission data for different vehicle types within a short time and at a relatively low cost. However, the major disadvantage of this technology is that it only gives an instantaneous estimation of emission concentration, which means that the mass of emissions cannot be obtained and the variation of emission rates under different driving modes and engine temperatures cannot be reflected. In order to evaluate the impact of traffic management strategies on mobile source GHG emissions, it is necessary to compare a vehicle's mass emissions for scenarios with versus without the implementation of a specific traffic management strategy in an area over an extended period of time. Therefore, RES technology is not directly applicable for this study.

2.1.4 Portable Emission Measurement System (PEMS)

PEMS was developed for emission inventory and regulatory applications in late 1990s under the lead of EPA. This measurement technology overcomes the limitations of chassis dynamometer, tunnel test, and RES by being able to measure emissions during the actual use of vehicles in their regular operations. It can collect the emission data on different road types, during different time periods, and for various types of vehicles in an easy and convenient manner. At present, one of the most advanced and representative PEMS products is OEM-2100 system developed by Clean Air Technologies International, Inc. (CATI). This system has been verified by EPA's Environmental Technology Verification (ETV) Program in 2003 for its precision and accuracy (Myers, Kelly, Dindal, Willenberg, and Riggs, 2003). The latest version is OEM-2100AX Axion. The Axion measures engine data using a set of sensors and reports engine and vehicle parameters from an engine control unit (ECU) interface. This unit is capable of collecting gaseous variables, including CO, CO_2, HC, NO_X, O_2, particulate matter (PM), and fuel consumption on a second-by-second basis and supports real time text and graphic display. In addition, a global positioning system (GPS) is included to provide the information about the testing vehicle's location and movement (CATI, 2008). The research in this study is based on the data collected by OEM-2100AX Axion.

2.2 Mobile Source GHG Emission Models

Existing research on mobile source GHG emission modeling approaches involves a wide use of GHG emission models. Some of the models are designed to develop emission factors for pollutants emitted during vehicles' use, such as MOBILE6, NONROAD, NMIM, EMFAC, and CLIP; and some take into consideration not only tailpipe emissions but also pre-combustion emissions, such as GREET, LEM, and MOVES. Many of these models are developed by EPA, but they vary significantly in terms of their capabilities, the level of sophistication, the type of inputs, and the scope of analyses.

2.2.1 MOBILE6 Model

MOBILE6 was developed by EPA to estimate current and future emissions from highway motor vehicles. It has been widely used in transportation analysis at national, state, and regional levels to evaluate highway mobile source emission control strategies, develop emission inventories, and assist transportation planning and conformity analysis. In addition to criteria pollutants, MOBILE6.1/6.2 includes the ability to estimate CO_2 emissions. Unlike most other MOBILE6 emission estimates, the CO_2 emission estimation is based on fuel economy performance. It does not account for the impacts of vehicle speed, temperature, fuel content, or the influence of vehicle I/M programs. This means that MOBILE6 cannot be used to model the effects on CO_2 emissions by varying these parameters, and it also means that this way of CO_2 emission estimation should only be used to model areas and time periods that are large or long enough to reasonably assume that the variation in these parameters does not have a significant net effect (EPA, 2003).

2.2.2 NONROAD Model

NONROAD model is an EPA approved model used to calculate past, present, and future emission inventories for all nonroad equipment categories, such as recreational vehicles, logging equipment, agricultural equipment, construction and industrial equipment, and residential and commercial lawn and garden equipment. This model estimates emissions for six exhaust pollutants, including HC, NO_X, CO, CO_2, sulfur oxides (SO_X), and PM. The user may select a specific geographic area (i.e., national, state, or county) and time period (i.e., annual, monthly, seasonal, or daily) for analysis. Fuel types included in the model are: gasoline, diesel, compressed natural gas, and liquefied petroleum gas. However, NONROAD model does not address commercial marine, locomotive, or aircraft emissions (EPA, 2005).

2.2.3 National Mobile Inventory Model (NMIM)

NMIM is a consolidated emissions modeling system for EPA's MOBILE6 and NONROAD models. It was developed to produce national, county-level mobile source emissions inventories for the National Emissions Inventory (NEI) and for EPA policy making. The model integrates the input data requirements, model runtimes, and post-processing requirements for both MOBILE6 and NONROAD models into a single package to provide consistency across both models, speed its operation, and minimize its output database size. However, NMIM cannot replace MOBILE6 and NONROAD models for all applications since it was designed primarily to generate national inventories (EPA, 2009b).

2.2.4 Emission FACtors Model (EMFAC)

The California Air Resource Board (CARB) developed EMFAC as the California version of MOBILE6. This model calculates emission factors and emission inventories for HC, CO, NO_X, CO_2, PM, SO_X, Lead (Pb), and fuel consumption from all the motor vehicles operating on the roads in California. Based on emission factors and vehicle activity inputs, this model generates emission estimates that can be used to develop emission inventories and conduct other project level analyses. However, even though EMFAC develops CO_2 and CH_4 emission estimates, CARB is currently using fuel usage information instead of EMFAC as the basis for its official GHG inventory (CARB, 2007), because researchers in CARB found that there is a difference between the reported number of gallons of fuel sold by the Board of Equalization and the estimated number of gallons extrapolated using EMFAC model. The research on how to resolve this discrepancy is still undergoing (Matute, 2010).

2.2.5 Climate Leadership in Parks (CLIP) Model

This model is a Microsoft Excel-based application developed by INF International for EPA and the National Park System. It is capable of estimating GHG and criteria pollutant emissions at the local level for all on-road and off-road transportations. CLIP model consists of two modules and each of them performs a distinct function. Generally speaking, Module 1 is an emission inventory module, which estimates GHG emissions from park sources and sums these emissions estimates to produce an inventory. Module 2 is an action planning module, which allows users to investigate ways to reduce emissions. Although the default vehicle characteristics are geared towards travel situations in national parks, users can also enter additional data to reflect vehicle emissions under local conditions (NPS 2009; Grant et al, 2008).

2.2.6 Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model

GREET model is developed by Argonne National Laboratory to evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels. This model includes more than 100 fuel production pathways and covers a wide range of vehicle technologies from conventional spark-ignition engine to fuel cell vehicles. For a given vehicle and fuel system, GREET separately calculates emissions of criteria pollutants, emissions of CO_2 equivalent GHGs, primarily CO_2, CH_4, and N_2O, and the consumption of total energy and fossil fuels (ANL, 2009).

2.2.7 Lifecycle Emissions Model (LEM)

LEM is a comprehensive model developed by Mark Delucchi at the University of California, Davis. It estimates energy use, criteria pollutants, and CO_2-equivalent GHG emissions from a variety of transportation modes, energy sources, and technologies. The LEM was one of the first such models developed for transportation. The current version includes input data from 1970 to 2050 for up to 30 countries. The user specifies a country, and then the model looks up the corresponding data sets and uses them to calculate emissions (Delucchi, 2002).

2.2.8 Motor Vehicle Emissions Simulator (MOVES)

MOVES is EPA's new generation emission model designed to estimate air pollution emissions from mobile sources. The latest version MOVES2010 incorporates substantial new emissions test data and accounts for changes in vehicle technology and regulations. It also improved the understanding of in-use emission levels and factors that influence them. MOVES2010 replaces MOBILE6.2 to estimate exhaust and evaporative emissions as well as brake and tire wear emissions from all types of on-road vehicles. It derives emissions estimates based on second-by-second vehicle performance for various driving modes, which allows the model to estimate emissions at different levels ranging from individual transportation projects to large regional emission inventories in a more accurate way. At present, it is the best tool EPA has for estimating GHG emissions from the transportation sector (EPA, 2010f, EPA, 2010g).

2.2.9 Other Models

Besides the most prevalent GHG emission models discussed above, there are many other models that are designed to address GHG emissions. Such models include State Inventory Tool (SIT) COMMUTER model, National Energy Modeling System (NEMS), VISION, World Energy Protection System (WEPS) Transportation Energy Model (TEM), and Systems for the Analysis of Global Energy Markets (SAGE) (Grant et al., 2008). However, these models are designed either for national- or state- level GHG emissions analysis, or predicting energy consumption based on various economic factors. They often do not account for complex implications of vehicle operating characteristics on emissions, therefore cannot be readily used for project-level analyses.

2.3 Air Quality Benefit Assessment of Traffic Management Strategies

With the aid of available GHG emissions measurement technologies and various GHG emission models, extensive research efforts have been made to assess the impact of traffic management strategies on GHG emissions. Major traffic management and control measures that have been investigated in terms of their impact on vehicles' CO_2 emissions include HOV lane, bus exclusive lane, traffic signal coordination plan, and ETC.

2.3.1 HOV Lane

Krimmer and Venigalla conducted an experimental study in the metropolitan Washington D.C. area to compare the testing vehicles' emissions on HOV lanes and mixed-flow (MF) lanes (Krimmer and Venigalla, 2006). In their research, several hundred miles of on-road emissions data were collected using PEMS by running pairs of nearly identical instrumented vehicles simultaneously on the HOV and MF facilities. A major finding was that higher speeds in HOV lanes resulted in higher emissions in most cases, except for CO_2. Total CO_2 emissions were inversely related to speed, the higher the mean speed a vehicle was able to maintain, the less the total CO_2 was emitted. However, this finding was applicable only to the specific vehicle used in the experiment and was limited by various testing conditions.

Boriboonsomsin and Barth have conducted a series of research on evaluating the air quality benefits of HOV Lanes (Boriboonsomsin and Barth, 2007). In 2007, they examined the operational differences in traffic dynamics between HOV lanes and MF lanes in Southern California and calculated the CO_2 emissions and fuel consumptions using the Comprehensive Modal Emissions Model (CMEM). The results indicated that on congested freeways, vehicles traveling in HOV lanes produce about 35 percent less CO_2 emissions than those traveling in MF lanes due to a better flow of traffic in HOV lanes; while on uncongested freeways, although higher emission and fuel consumption rates are produced on HOV lanes due to higher speeds, VMT in HOV lanes are much lower, which resulted in a lower emissions mass on a per lane basis. In 2008, Boriboonsomsin and Bath estimated and compared vehicle emissions contributed from continuous access HOV lanes and limited access HOV lanes with a combined use of microscopic traffic model PARAMICS and the microscopic emission model CMEM. It was found that the limited access HOV lanes contribute to higher amount of emissions due to more frequent and aggressive acceleration/deceleration maneuvers occurring at the dedicated ingress/egress sections. The amount of CO_2 emissions were increased by three to eight percent (Boriboonsomsin and Barth, 2008). In 2009, based on the scientific investigation of the differences between HOV lanes and MF lanes in terms of their vehicles' speed and acceleration profiles and their fleet composition, HOV lane emission correction factors were developed for the prevailing speed ranging from 25 to 105 kilometers per hour (kph) to generate emission rates that are specific for HOV lanes. The analysis results showed that HOV lanes have higher impact on the emission rate of CO_2 as compared to HC and NO_X (Boriboonsomsin, 2009).

2.3.2 Bus Exclusive Lane

Guo and Yu investigated the impact of installing different types of bus exclusive lanes on vehicle emissions (Guo and Yu, 2010). In their study, PEMS data were collected and analyzed to reflect the vehicle's driving and exhaust emission characteristics and traffic simulation model VISSIM was used to model different design schemes of bus exclusive lanes including central bus lanes, curb bus lanes, and no bus lanes. This research estimated and compared total CO_2 emissions as well as emission intensities at different time periods and around interchanges for different design schemes. Results showed that CO_2 emissions were reduced by about six percent and one percent after the installation of central bus lanes and curb bus lanes respectively.

2.3.3 Traffic Signal Control Plans

Rakha and Ding (Rakha and Ding, 2003) evaluated the impact of vehicle stops on fuel consumption and emission rates with the real-world acceleration/deceleration data collected along a signalized arterial corridor using GPS-equipped vehicles. The study found that vehicle fuel consumption and emission rates increased considerably as the number of vehicle stops increased, especially at high cruise speeds. In addition, vehicle's fuel consumption was more sensitive to the cruise speed level than to vehicle stops.

With a combined use of microscopic traffic simulator VISSIM, microscopic emission estimation model CMEM, and stochastic signal optimization tool VISGAOST, Stevanovic et al. examined a 14-intersection network in Park City, Utah, for the purpose of providing signal timings that minimize vehicles' fuel consumption and CO_2 emissions. Results of the research showed that after the signal optimization, estimated fuel savings and CO_2 reduction were around one and a half percent (Stevanovic et al., 2009).

2.3.4 Electronic Toll Collection

Bartin et al. (Bartin et al., 2007) presented a microscopic simulation based estimation of the spatial-temporal change in air pollution levels as a result of ETC deployment in New Jersey Turnpike (NJTPK), in which overall impacts, location-based impacts, short-term and long-turn impacts of ETC system were compared. At each time step of the mobile source GHG emission simulation, vehicles' CO_2 emissions were calculated for each vehicle type based on their speeds using the macroscopic emission model MOBILE6.2. Results showed that the ETC deployment reduced overall CO_2 emissions on the network in the short term; however, its long-term benefits were not sufficient enough to compensate the increase of CO_2 emissions on the mainline due to the annual traffic growth.

Song et. al (Song, et. al., 2008) analyzed the emissions around a toll station area in Beijng, China, using PEMS measurements. The real-world vehicle emission and driving activity data for a light-duty gasoline vehicle were collected simultaneously for both ETC and manual toll collection (MTC) lanes, and then the emission reductions resulted from ETC lanes were assessed based on the collected PEMS data. Comparison results showed that CO_2 emissions can be reduced by 48.9% by using ETC.

Coelho et. al. (Coelho, 2005) studied traffic and emission impacts of toll facilities in urban corridors. In this research, a methodology that can quantify the traffic performance at a toll facility with the conventional payment and ETC was developed. This research also explained the relationship between variables characterizing stop-and-go behavior with environmental and traffic performance variables, in particular, CO, NO, HC, CO_2, and queue length. The main conclusion of this work was that the greatest percentage of emissions for a vehicle that stops at a MTC station was due to its final acceleration back to the cruise speed after leaving the toll station. When there was a queue of 20 vehicles, vehicles' CO_2 emissions can be reduced by 70 percent after the implementation of ETC; while for a queue of only one (1) vehicle, the corresponding emission reduction was 11percent.

2.3.5 Others

Other traffic management strategies that have been investigated in terms of their impact on mobile source GHG emissions include demand control, banning heavy duty vehicles (HDVs), speed restriction, and adaptive cruise control (ACC). In a recent study conducted by Mahmond (Mahmond et al., 2010), the impact of these traffic control measures on vehicle emissions at a single intersection located at Bentinckplein in the city of Rotterdam, Netherlands was investigated with the help of traffic model VISSIM and microscopic emission model EnViVer. It was found that reducing traffic demand by 20 percent led to about 23percent CO_2 emission reduction; eliminating the number of HDVs resulted in a total reduction of 25.8 percent for CO_2; speed restriction can reduce CO_2 emissions by 10.7 percent for light duty vehicles (LDVs) and 5.6 percent for HDVs; and ACC reduced CO_2 by 3.5 percent and 1.8 percent for LDVs and HDVs respectively.

2.4 Summary

The literature review on mobile source GHG emission measurement methods, mobile source GHG emission models, and current research on air quality benefit assessment of traffic management strategies provides solid background knowledge about the accomplishments that have been achieved in this field and obstacles that exist in the current research, which gives insightful guide towards conducting the research for this study.

Accurate and abundant data is very important in the research of on-road emissions. With the ability of measuring second-by-second emissions during the actual use of vehicles in their regular operations, PEMS is of overwhelming advantage over other existing emission measurement technologies. Therefore, a PEMS device is used for the data collection in this research. Considering traffic conditions in Houston, as well as the popularity of traffic management strategies that have been selected in the existing motor vehicle emission studies, HOV lane, traffic signal coordination plan, and ETC are chosen as the target traffic management strategies in this research. In addition, based on the real-world data collected by PEMS, a VSP-based mobile source GHG emission modeling approach is developed as the basis for emission estimations. A detailed description about the design of this study is provided in the next chapter.

CHAPTER 3: DESIGN OF THE STUDY

3.1 General Methodology

In this research, the evaluation of traffic management strategies in terms of their effects on mobile source GHG emissions is fulfilled by a combined use of the field data collected by a PEMS device and a VSP-based modeling approach. Therefore, the general methodology includes comprehensive data collection, the application of state-of-the-art vehicle emission modeling approach, and a thorough evaluation of the selected traffic management strategies.

3.1.1 Data Collection Approach

Two parts of real-world data are needed to perform the proposed evaluation study. One part includes data collected for the purpose of developing the modeling approach that meets specific needs of the emission calculation in this study; and the other part includes data collected in the designed testing areas to facilitate the case-specific traffic management assessment.

The data used for the model development are collected by a light duty gasoline vehicle equipped with a PEMS unit. The data collection tests are performed on various road types during different time periods in different days in order to fully capture the testing vehicle's typical driving conditions in the traffic network in Houston.

The data collection for case-specific traffic management assessment is more complicated. It involves a circumspect design of testing scenarios and a careful consideration of testing vehicles, testing equipments, testing routes, and testing times and locations. The basic idea is to create data collection scenarios that are able to reflect real-world traffic conditions with versus without the implementation of specific traffic management strategies for the purpose of comparison and then to use real-world vehicle operational and emission data to perform the evaluation study.

3.1.2 Emission Modeling Approach

A VSP-based emission modeling approach is used in this research. VSP is defined as the tractive power exerted by a vehicle to move itself and its cargo or passengers using the unit of Kw/Metric Ton (Nam and Giannelli, 2005). It includes various information of the vehicle's operating mode characterization, such as acceleration, deceleration, breaking, and idle, and explains a substantial portion of variability in the fuel use and tailpipe emissions during a vehicle's real-world operation.

The calculation of VSP accounts for the power demand, rolling resistance, aerodynamic drag, and road grade. Based on coefficient values for a generic light duty vehicle, VSP can be calculated by Equation (1).

$$VSP = v \times [1.1a + 9.81 \times grade(\%) + 0.132] + 0.000302 \times v^3 \qquad (1)$$

Where:
v = vehicle speed, (*m/s*),
a = vehicle acceleration, (m/s^2), and
$grade$ (%) = vehicle vertical rise divided by the slope length.

Because almost all tests are conducted on flat roads, the road grade can be assumed to be zero. Therefore, Equation (1) can be simplified to:

$$\mathrm{VSP} = \mathrm{v} \times (1.1\mathrm{a} + 0.132) + 0.000302 \times \mathrm{v}^3 \qquad (2)$$

Merits of incorporating VSP into the emission modeling approach lie in (1) VSP has been consistently identified as the most important explanatory variable for the vehicle's exhaust emissions; (2) VSP can be easily obtained by needing only the vehicle's speed and acceleration; and (3) VSP has a good consistency with the fuel consumption (Yu et al., 2008; Frey et al. 2006).

3.1.3 Strategy Evaluation Approach

The evaluation approach is based on the calculation of emission reductions for scenarios with vs. without the implementation of a specific traffic management strategy. Since this research focuses on existing traffic management strategies, the testing vehicle's emissions and operational data in the real-world network can be directly collected using the PEMS equipment. In the meantime, the case-specific data collection plan needs to be developed so that the vehicle's emissions under the scenario without the implementation of the selected traffic management strategy can be calculated in the real-world setting. The VSP-based emission modeling approach makes it possible to perform emission calculations by needing only the vehicle's speed and acceleration, therefore, in this study, a vehicle equipped with a GPS device is used to run with the vehicle equipped with the PEMS unit in a synchronized way under different scenarios. In this way, a pair of paralleled datasets can be obtained for the purpose of comparison.

3.2 Data Collection Approach

3.2.1 Data Collection Equipment

Based on the review study on major GHG emission measurement methods, PEMS represents the most advanced GHG emission data collection technology and only the data collected by PEMS meets the requirements for this study. A GPS system is able to characterize a vehicle's driving behavior by recording second-by-second coordinates and provide a vehicle's speed in each second. GPS-based information will facilitate the data analysis in this research. Therefore, a PEMS unit and a GPS device are used as the data collection equipments for this study.

OEM-2100AX Axion Unit. OEM-2100AX Axion is utilized as the primary data collection equipment. This unit uses USEPA verified GHG monitoring technology and is an EPA verified PEMS unit designed to measure real-time vehicle mass exhaust emissions using vehicle and engine operating data and concentrations of pollutants in the exhaust gas sampled from the tailpipe (EPA, 2009c). This equipment consists of four main subsystems: computer, engine data acquisition module, PM monitor, and dual gas analyzers. It is capable of reporting emissions, vehicle speed, engine resolution per minute (RPM), and temperature in second-by-second resolution and calculating fuel consumption and exhaust flow. An embedded GPS system provides geographic location information for the testing vehicle at all times (CATI, 2008).

The Axion unit may be placed at a safe and easy to access place in or on the testing vehicle. The power is drawn from the vehicle power socket or from a cable clamped directly onto the vehicle battery. For in-vehicle installation, the exhaust sample lines can be routed through a window and secured to the exhaust system using hose clamps. The operation of the system involves warming up the equipment before the test, entering correct setup parameters, and checking data for correct ranges during the on-road test. Figure 1 displays a selection of pictures taken during an Axion-based emission test.

Axion Installed in the Vehicle

Data Collection Operation Interface

Exhaust Sample Line Secured to the Exhaust System

Routing of the Exhaust Sample Lines

Figure 1 Selected Pictures during an Axion-based Emission Test

GeoLog GPS Device. A GeoLog GPS device is used to collect the testing vehicle's position and speed information at each second. The device receives power from the vehicle's cigarette lighter outlet and is placed under the front windscreen to improve its acquisition of the signal from satellites. Figure 2 shows the GeoLog GPS device used during the test.

GeoLog GPS Used for the Test

GeoLog GPS Installed in the Vehicle

Figure 2 GeoLog GPS Device Used in the Test

3.2.2 Data Screening

Due to rough road conditions, random errors may occur during data collection using the PEMS unit, and data losses and errors also happen to the GPS data especially when vehicles are driven under bridges or through high buildings, therefore, it is necessary for the raw data to go through a data quality assurance procedure to ensure that only valid data are used in the subsequent analysis.

Data collected by the PEMS are automatically saved in the computer embedded in the unit in *.txt files. Files are then exported into excel files for further review. In order to ensure the completeness and accuracy of the PEMS data, all data records are screened based on the following procedure: (1) review the "valid_g/s" column to make sure that the information was recorded; (2) review the reported status of each gas bench to make sure that two gas benches reported similar values of the exhaust component; (3) review the values of engine operating parameters, such as RPM, in take air temperature, manifold air pressure, and speed, to make sure that the data are complete and consistent; (4) check engine RPM to make sure that variations are reported every few seconds; and (5) compare engine operating parameters with its conventional minimum and maximum values to determine if there are any irregular data points (CATI, 2008). A dedicated Macro in Excel is used to eliminate all invalid data.

The most common errors found in the GPS data are data losses and the data deviation caused by the short term signal block or interference. Therefore, a computer program is developed to remove deviated data points and smooth the dataset.

3.2.3 Database Establishment

The screened data are processed and then imported into a database developed using Microsoft ACCESS 2007. This database currently contains three tables: EMISSION table, VEHICLE table, and DRIVER table. The EMISSION table stores second-by-second test data including testing date, time, engine RPM, in take air temperature (IAT), manifold air pressure (MAP), gas analyzer source, fuel consumption, volume and mass of exhaust pollutants, including CO_2, CO, HC, and NO_X, vehicle's speed, acceleration, location, bearing, and ambient environmental condition, such as temperature, pressure, and relative humidity. The VEHICLE table stores the testing vehicle' information and route information, such as vehicle make, model, engine placement, year, age, mileage, fuel type, and road types that driving routes cover. The DRIVER table records the driver's name, age, gender, occupation, years of driving, and contact information. These three tables are interconnected. For example, if a second-by-second emission data is located, all the relevant information from other tables can be retrieved according to the testing date.

3.3 VSP-based GHG Emission Modeling Approach

The basic methodology for developing the VSP-based emission modeling approach is binning second-by-second VSP data and computing the average emission rate in each bin. The meaning of each bin is the percentage of corresponding VSP values in the whole distribution, which captures unique emissions for that emission process. With this partition, the average emission rate of a particular type of pollutant in that bin for a specified vehicle can be determined.

The accuracy of the VSP-based modeling approach relies on how VSP bins are defined. However, there has been no clear definition about criteria in selecting VSP cutting points, therefore, the definition of VSP bins embedded in MOVES is used in the binning process in this study, since MOVES is currently considered the standard tool that EPA has for estimating GHG emissions from the transportation sector (EPA, 2010g). On the basis of VSP, speed, and acceleration, a total of 17 operating modes are defined for running energy consumption for motor vehicles in MOVES (EPA, 2010h). The definition of MOVES operating mode attributes for running energy consumption is reorganized into Table 1 according to EPA's guide on the emission rate development for light duty vehicles in MOVES (EPA, 2010i). It shows that, aside from braking, which is defined in terms of the acceleration alone, and idle, which is defined in terms of the speed alone, the remaining 15 modes are defined in terms of VSP within broad speed classes.

Table 1 Definition of MOVES Operating Mode Attributes for Running Energy Consumption

Operating Mode	**Operating Mode Description**	**VSP (VSPt, kW/T)**	**Vehicle Speed (Vt, mi/hr)**	**Vehicle Acceleration (a, mi/hr-sec)**
0	Deceleration/ Braking			$a_t \leq$ -2.0 OR ($a_t <$ -1.0 AND $a_{t-1} <$ -1.0 AND $a_{t-2} <$ -1.0)
1	Idle		$-1.0 \leq v_t < 1.0$	
11	Coast	$VSP_t < 0$	$0 \leq v_t < 25$	
12	Cruise/Acceleration	$0 \leq VSP_t < 3$	$0 \leq v_t < 25$	
13	Cruise/Acceleration	$3 \leq VSP_t < 6$	$0 \leq v_t < 25$	
14	Cruise/Acceleration	$6 \leq VSP_t < 9$	$0 \leq v_t < 25$	
15	Cruise/Acceleration	$9 \leq VSP_t < 12$	$0 \leq v_t < 25$	
16	Cruise/Acceleration	$12 \leq VSP_t$	$0 \leq v_t < 25$	
21	Coast	$VSP_t < 0$	$25 \leq v_t < 50$	
22	Cruise/Acceleration	$0 \leq VSP_t < 3$	$25 \leq v_t < 50$	
23	Cruise/Acceleration	$3 \leq VSP_t < 6$	$25 \leq v_t < 50$	
24	Cruise/Acceleration	$6 \leq VSP_t < 9$	$25 \leq v_t < 50$	
25	Cruise/Acceleration	$9 \leq VSP_t < 12$	$25 \leq v_t < 50$	
26	Cruise/Acceleration	$12 \leq VSP_t$	$25 \leq v_t < 50$	
33	Cruise/Acceleration	$VSP_t < 6$	$50 \leq v_t$	
35	Cruise/Acceleration	$6 \leq VSP_t < 12$	$50 \leq v_t$	
36	Cruise/Acceleration	$12 \leq VSP_t$	$50 \leq v_t$	

3.4 Traffic Management Scenario Design

HOV lane, traffic signal coordination plan, and ETC are chosen as the target traffic management strategies for the analysis in this study. Detailed data collection plans are made to create data collection scenarios that are able to reflect real-world traffic conditions with versus without the implementation of the selected traffic management strategies.

3.4.1 Scenario Design for HOV Lane Analysis

There are five major HOV lanes in the Houston area. Based on five consecutive days' observation on the live traffic on those HOV lanes from Houston TranStar, it is found that the HOV lane on IH-45 North (I-45 N) experiences the biggest traffic demand during afternoon peak hours. Therefore, a freeway segment on I-45 N is selected as the study area. The map of the study area is shown in Figure 3. In addition, according to Houston TranStar Speed Charts falling into the selected road segment, shown in Figure 4, the lowest travel speed usually occurs around 5:30 P.M. to 6:30 P.M., therefore, the data collection for HOV lane analysis is conducted during this time frame.

Under this scenario, CO_2 emission factors obtained on the selected road segment using HOV lane and mixed flow (MF) lane are compared. Two light duty gasoline vehicles are used for the data collection, one equipped with a PEMS unit and the other one equipped with a GPS device. The data collection is performed on two different days. On the first day, the vehicle equipped with the PEMS unit drives on the designated HOV lane and the vehicle equipped with the GPS device drives in parallel on the corresponding MF lane, and then two vehicles switch their roles on the second day of the test. Because the vehicle that runs on the HOV lane requires less travel time to arrive at the selected exit of the freeway, in order to achieve a better synchronization, it is designed that the vehicle drives on the MF lane enters the testing road segment about 10 minutes earlier than does the vehicle that drives on the HOV lane.

Figure 3 Study Area for HOV Lane Analysis
Source: http://www.ridemetro.org/SchedulesMaps/HOV/i45n.aspx

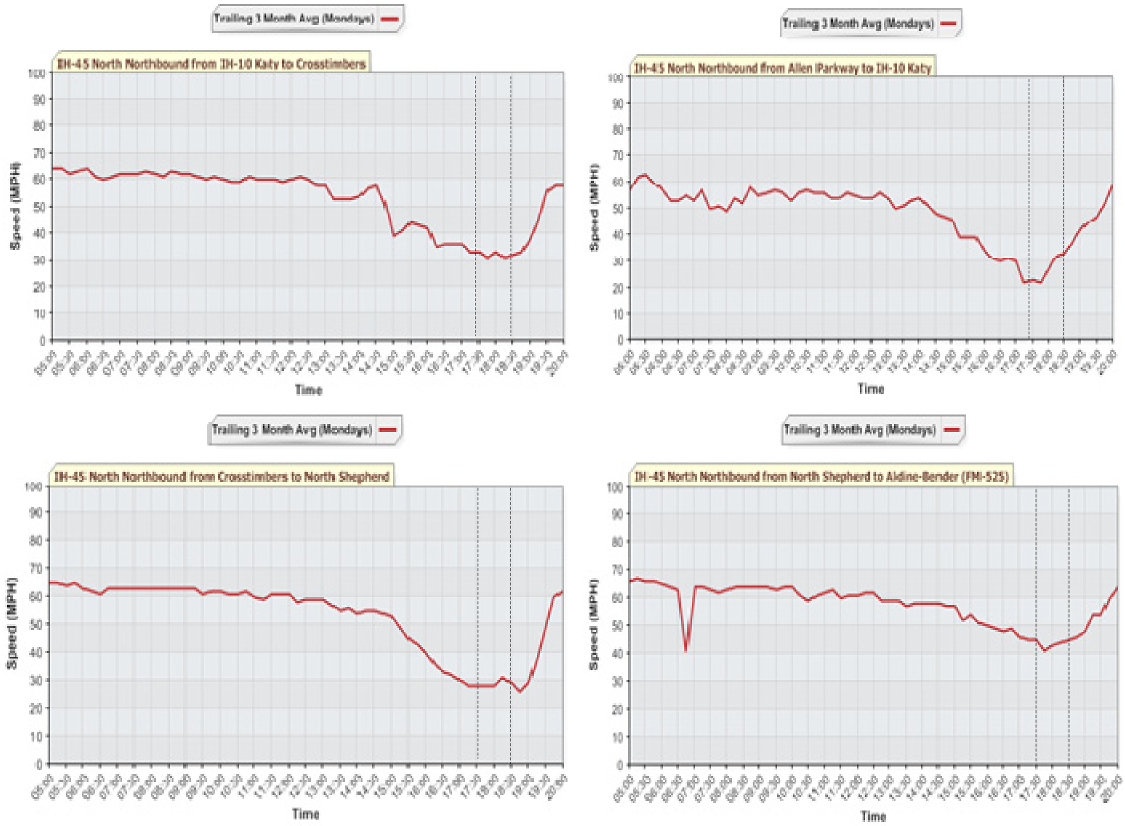


Figure 4 3-Monthly Average Speed on the Selected Freeway Segment on I-45 N
(The beginning and ending of the test time periods are indicated by dash lines)
Source: http://traffic.houstontranstar.org/speedcharts/

3.4.2 Scenario Design for Traffic Signal Coordination Analysis

It is observed that the signal timing in Houston Downtown Area is well coordinated. When driving at about 25-30 miles per hour (mph), the existing traffic signal timing allows vehicles to pass through several consecutive intersections without being interrupted by red lights. Therefore, a route composed of four one-way streets in Downtown Houston is selected as the testing area for this study. As shown in Figure 5, these streets form a closed loop with seven intersections on Webster St. and Pease St. (east and west bound) respectively and four intersections on Crawford St. and Milam St. (north and south bound) respectively excluding four turning intersections. The total distance of the testing route is about 2.9 kilometers, in which each pair of adjacent intersections is approximately 75 meters apart.

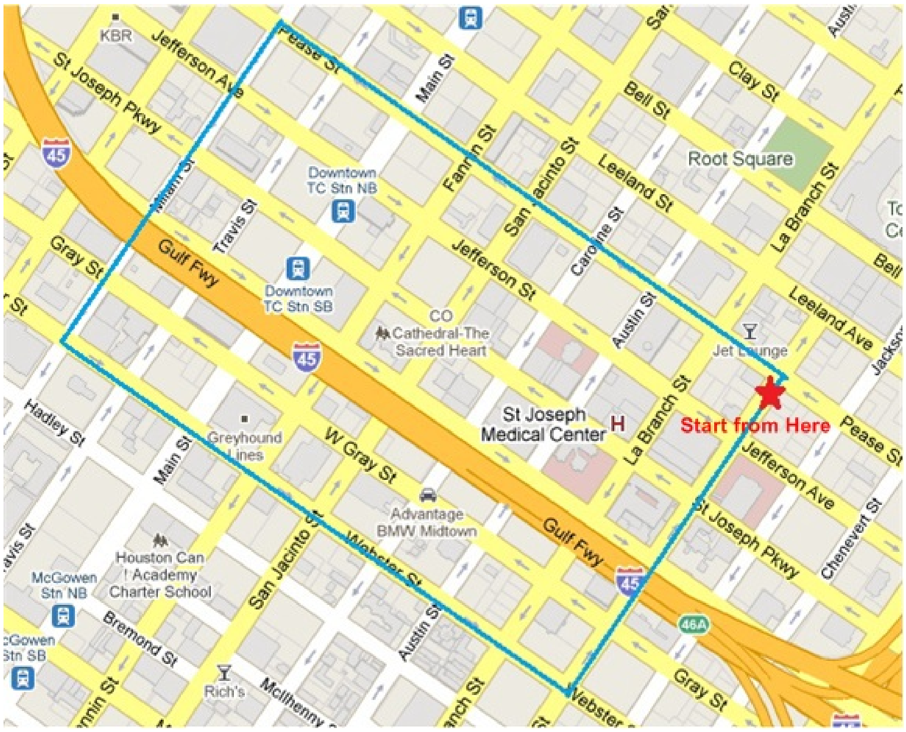


Figure 5 Study Area for Signal Coordination Analysis

Data are collected using two light duty gasoline vehicles, one equipped with a PEMS unit and the other one equipped with a GPS device. These two vehicles take turns running under two testing scenarios: (1) following the existing coordinated signal timing; and (2) following the emulated non-coordinated signal timing by making random stops in front of green lights purposely. The intersection Crawford St. at Pease St. is used as the starting point. Two testing vehicles always meet at this point at the end of each cycle and leave this point simultaneously at the beginning of a new cycle. It is designed that both testing vehicles repeat the driving along the testing route eight times with four times following the existing coordinated signal timing and four times making random and purposive stops in front of green lights. The type, time, and location of every stop that testing vehicles made were recorded by a designated person in the vehicle. This information can facilitate data processing in the result analysis.

Two trial tests are performed before the real test. It is found from the field inspection that all vehicles on selected streets share the side lanes for through traffic, regulated turning movements, and roadside parking, therefore, it is feasible to randomly and purposely stop the testing vehicle in front of green lights without leaving the regular lane, while at the same time without generating too much disturbance on passing vehicles.

3.4.3 Scenario Design for ETC Analysis

Under this scenario, the amount of CO_2 emissions that a vehicle produces around an ETC station and a Manual Toll Collection (MTC) station in the same network are compared. After a careful examination of the type and location of all toll stations in Houston, a segment on Fort Bend Parkway Toll Road is selected as the testing area. As shown in Figure 6, there are two toll stations along the selected road segment, the one located in the North accepting both electronic tolling (pay by a pre-purchased Easy Tag) and manual tolling (pay by coins), which, however, is always used as an MTC station for this study; and the one located in the South is an ETC station, which can only be paid by Easy Tag.

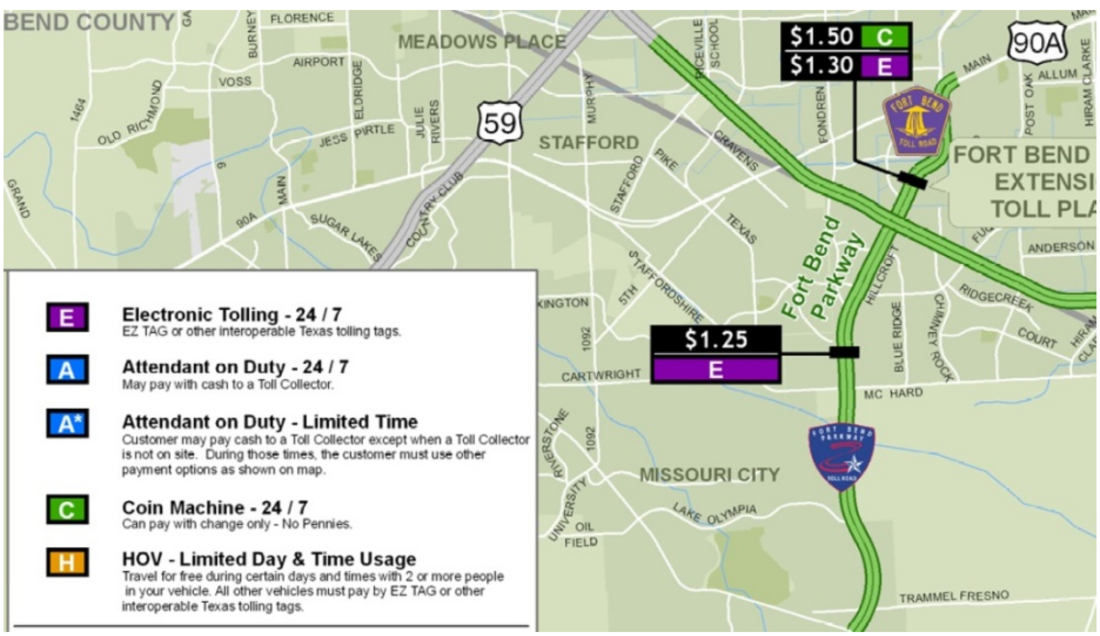


Figure 6 Study Area for ETC Analysis

Source: *https://www.hctra.org/files/Front_SW_Quadrant.pdf*

A light duty gasoline vehicle equipped with a PEMS unit is used as the testing vehicle. During the data collection, after the vehicle enters the selected toll road segment, it first stops and pays manually at the MTC station, and then passes through the ETC station with an automatic Easy Tag payment. After that, the testing vehicle exits the toll road and makes a U-turn to enter the opposite direction of the same road segment. After the testing vehicle passes the same ETC and MTC stations for a second time, it leaves the toll road from the nearest exit and starts a new cycle. It is planned to drive five cycles along the testing route so that 10 sets of the vehicle's emission, operation, and movement data can be collected around the MTC and ETC stations respectively. The total distance is about 10 miles per cycle.

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter presents the application of the VSP-based emission modeling approach and the results generated from the analysis of real-world data collected under each traffic management scenario. An evaluation of the selected traffic management strategies in terms of their effects on mobile source GHG emissions is discussed based on the data analysis results.

4.1 Development and Validation of the Proposed Modeling Approach

4.1.1 Data Source

The data utilized for the development of the GHG emission modeling approach were collected during eight different days from April to July 2010 in Houston, covering different time periods of the day and various road types. A 1999 Nissan Altima was recruited as the testing vehicle and was equipped with the PEMS Unit. Detailed information about the testing vehicle is listed in Table 2. In addition, in order to minimize the influence from individual driver's driving behavior, the same driver was used for all tests. After the data screening, a total of 35,538 data records are left and imported into a database. The whole dataset is then divided into two parts, one for the model development and another one for the model validation.

Table 2 Information about the Testing Vehicle for Model Development

Make and Model	Nissan Altima
Engine Displacement	2.4 L
Year	1999
Age	11
Mileage	71600
Fuel Type	Gasoline-petrol
Transmission	4-speed automatic
Horsepower	110.4kw @ 5600 RPM
Weight	2925 lbs
Length	183.5 in

4.1.2 Development of the Proposed Modeling Approach

A total of 18,253 data records are used for the development of the modeling approach. Based on the second-by-second speed and acceleration data, VSP values are computed using Equation (2), and then a computer program is executed to bin these values based on the definition of VSP bins used in MOVES. Figure 7 illustrates the average CO_2 emission rate and data frequency for each VSP Bin. Table 3 lists the value of the average CO_2 emission rate each bin represents. Because a vehicle's emission rate for a certain exhaust pollutant is mainly determined by the vehicle's technologies, it is a fixed value under different driving conditions. Therefore, the resulted CO_2 emission rates for each bin can be readily used to calculate aggregated mass emissions that each bin represents in the model application.

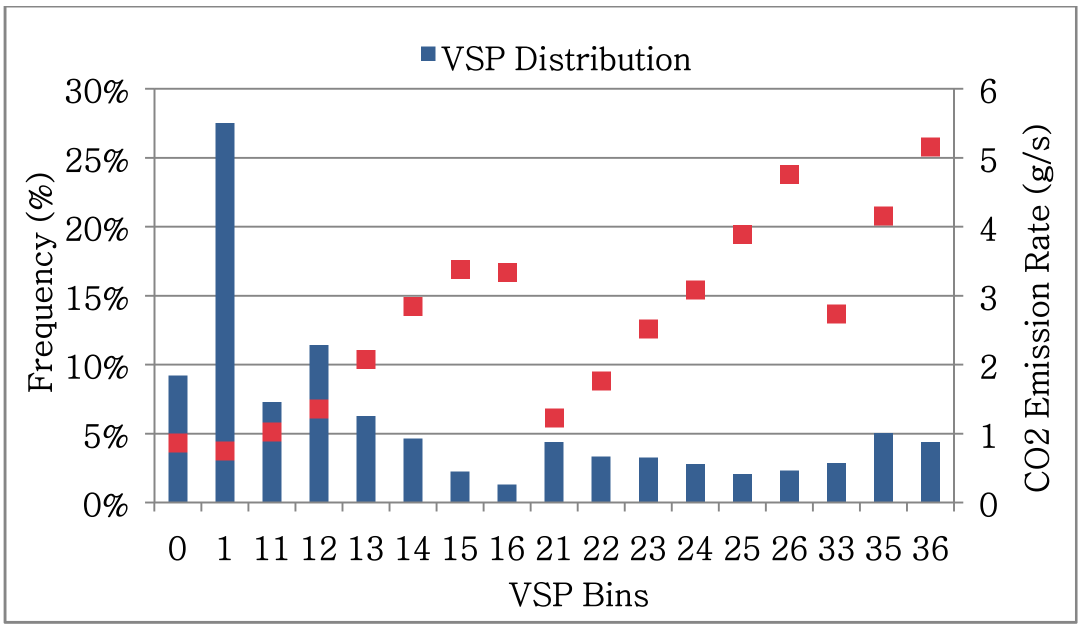


Figure 7 Average CO_2 Emission Rate and Data Frequency for Each VSP Bin

Table 3 Average CO_2 Emission Rate for Each Bin

Bin #	Emission Rate (g/s)	Bin #	Emission Rate (g/s)
Bin 0	0.860987	Bin 21	1.222702
Bin 1	0.747978	Bin 22	1.757108
Bin 11	1.022136	Bin 23	2.517369
Bin 12	1.351904	Bin 24	3.077797
Bin 13	2.071827	Bin 25	3.886606
Bin 14	2.841045	Bin 26	4.753380
Bin 15	3.374991	Bin 33	2.730084
Bin 16	3.338543	Bin 35	4.155850
-	-	Bin 36	5.156085

4.1.3 Validation of the Proposed Modeling Approach

A total of 17,285 data records are used for the model validation. Because PEMS records a vehicle's real-world CO_2 mass emissions in grams per second, the total CO_2 emissions produced by this part of data over the covered time period can be directly calculated by summing up the collected grams per second emission data. Based on the VSP binning approach introduced in the model development, the number of data points that fall into each bin for this part of data can be obtained. With the use of the average CO_2 emission rate shown in Table 3, the total CO_2 emissions produced over the covered time period can also be calculated based on the modeling approach.

Table 4 lists the average CO_2 emission rate generated from the modeling approach, the number of VSP data falling into each bin, and the total CO_2 emissions produced by each bin. The results show that the total CO_2 emissions collected by the PEMS and generated from the VSP-based modeling approach are 35173.046 grams versus 31810.2949 grams respectively over the same covered distance. The relative difference is 9.56 percent.

The comparative analysis shows that the level of accuracy of the proposed GHG emission modeling approach reaches over 90 percent. Therefore, this modeling approach can be readily used to estimate mobile source CO_2 emissions for the traffic management assessment in this study.

Table 4 Comparison of Total CO_2 Emissions Based on Modeling Approach and PEMS Emission Data

Bin ID	Average CO2 Emission Rate from Modeling	Number of Data in Each Bin	Emission in Each Bin from Modeling (g)
0	0.8610	1660	1429.2384
1	0.7480	4468	3341.9657
11	1.0221	1327	1356.3745
12	1.3519	1924	2601.0633
13	2.0718	1158	2399.1757
14	2.8410	952	2704.6748
15	3.3750	401	1353.3714
16	3.3385	129	430.6720
21	1.2227	823	1006.2837
22	1.7571	803	1410.9577
23	2.5174	617	1553.2167
24	3.0778	521	1603.5322
25	3.8866	438	1702.3334
26	4.7534	340	1616.1492
33	2.7301	363	991.0205
35	4.1559	707	2938.1860
36	5.1561	654	3372.0796
Total Emissions from Modeling Approach			**31810.2949**
Total Emission from PEMS Emission Data			**35173.0460**
Relative Difference			**9.56%**

4.2 Evaluation and Analysis of HOV Lane Scenario

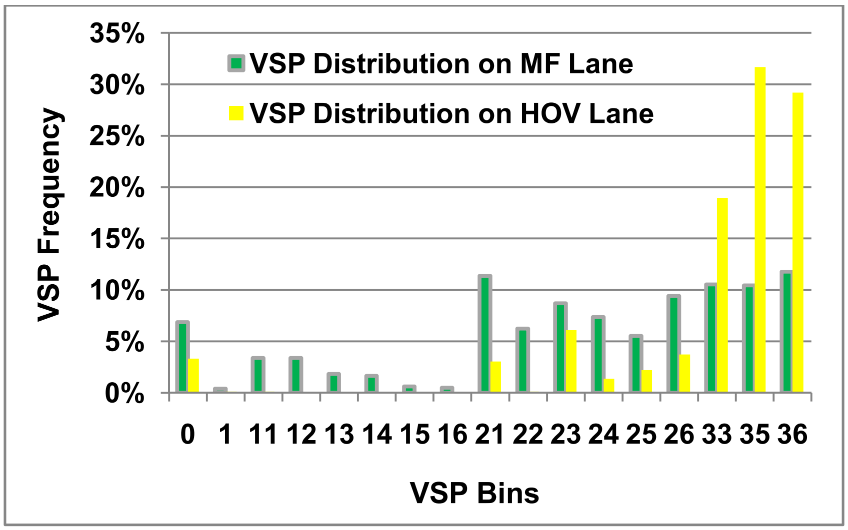
According to the scenario design for HOV lane analysis, the data utilized for HOV lane evaluation are collected between 5:30 P.M. to 6:30 P.M. on July 6 and 12, 2010 on the selected freeway segment along I-45 N. The same 1999 Nissan Altima is used as the testing vehicle, which is equipped with the PEMS. On July 6, this testing vehicle drove on the selected freeway segment using HOV lane, and at the same time, a second vehicle equipped with a GPS device drove in parallel with the PEMS vehicle on the corresponding MF lane. Two vehicles switched their roles on the second day of the test. Because the vehicle equipped with the GPS device always runs in a synchronized way with the vehicle equipped with the PEMS, and only the speed data collected by the two equipments are involved in the emission estimation based on the VSP-based modeling approach, the resulting values are comparable.

With a combined use of Google Map and the geographic coordinates recorded in the PEMS unit and the GPS device, a point close to the HOV lane entrance on the MF lane is marked as the start point of the target freeway segment; and another point along the exit ramp where both testing vehicles will pass is selected as the end point. After a data quality assurance procedure, on the first testing day, a total of 723 PEMS data and 977 GPS data are selected; and on the second testing day, a total of 707 GPS data and 1,228 PEMS data are selected. Table 5 shows the resulting CO_2 emission factors on the selected freeway segment using HOV lane and the corresponding MF lane. It is shown that on the first day, CO_2 emission factors generated by the testing vehicle on the HOV lane and the corresponding MF lane are 249.55 g/mile and 258.75 g/mile respectively, so the results show that the emission reduction rate by using HOV lane is about 3.56 percent; on the second day, the resulting CO_2 emission factors on the HOV lane and the MF lane are 247.15 g/mile and 275.90 g/mile respectively, so about 10.42 percent CO_2 emissions is reduced by using HOV lane.

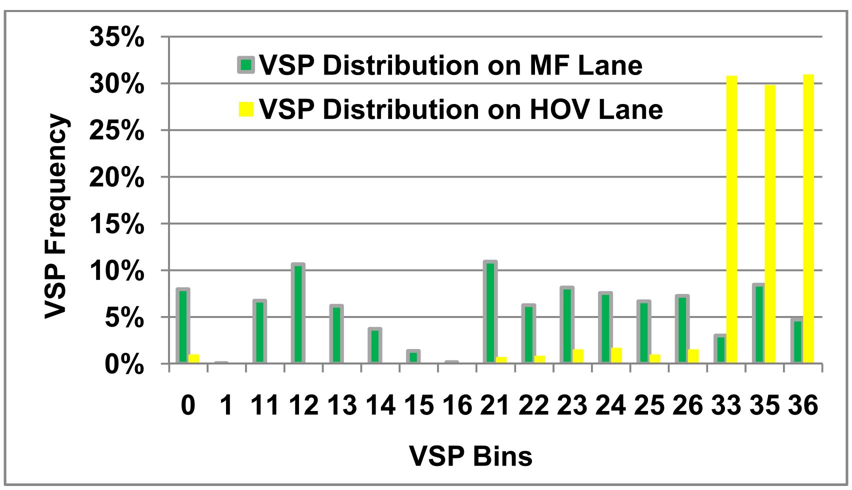
Table 5 Comparison of CO_2 Emission Factors Using HOV Lane and MF Lane

	Total CO_2 Emissions (g)		**Total Distance Traveled (mile)**		**CO_2 Emission Factor (g/mile)**	
	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
Using HOV Lane	2797.41	2768.03	11.21	11.20	249.55	247.15
Using MF Lane	2882.43	3110.40	11.14	11.27	258.75	275.90
Amount of CO_2 Emissions Reduced Using HOV Lane					9.20	28.75
Percentage of CO_2 Emissions Reduced Using HOV Lane					3.56%	10.42%

The difference of emission reductions is mainly due to different traffic demands on the MF lane in the two testing days. Figure 8 shows the VSP distributions on the HOV lane and the corresponding MF lane resulted from the two experimental tests. Based on the speed classification in the VSP definition, Bin 0 and Bin 1 represent the breaking and idling respectively, Bins 11 to 16 refer to the speed range 0-25 mph, Bins 21 to 26 refer to the speed range 25-50 mph, and Bins 33, 35, and 36 refer to the speed higher than 50 mph. This figure reflects that when the vehicle drives on the HOV lane, about 80% data fall into Bins 33, 35, and 36. When the vehicle drives on the corresponding MF lane, the data falling into these three bins are significantly reduced. On Day 1, about 33 percent of the total data are in Bins 33, 35, and 36, and only 11 percent of the total data are in Bins 11-16; while on Day 2, the data falling into Bins 11-16 increased to 29 percent, and the data falling into Bins 33, 35, and 36 decreased to 16 percent. Therefore, we can see that the vehicle's average speed is lower in the second day of the test, which also means that the selected segment of the MF lane is more congested on Day 2.



Resulted from the Test on July 6, 2010



Resulted from the Test on July 12, 2010

Figure 8 Comparisons of VSP Distributions on HOV Lane and MF Lane

The above comparative analysis demonstrated that during peak periods, the testing vehicle produces less CO_2 emissions mass per mile by using HOV lane. The more traffic demand on the corresponding MF lane, the more CO_2 emissions can be reduced by using HOV lane. In addition, since only a vehicle with a driver plus at least one passenger is allowed to use HOV lane, HOV lane has the potential to further reduce a vehicle's emissions by affecting the total vehicle miles traveled. Take the results generated from this study as an example: there is one driver and one passenger in the vehicle running on the HOV lane, if these two persons drove their own individual vehicles separately on the MF lane during the same testing period, then the amount of CO_2 emissions reduced by using HOV lane can be doubled.

4.3 Evaluation and Analysis of Traffic Signal Coordination Scenario

The data utilized for the evaluation of the signal coordination plan was collected between 3:00 P.M. and 5:00 P.M. on June 17, 2010 in Downtown Houston. The same 1999 Nissan Altima is equipped with the PEMS. In addition, a 2002 Ford Taurus is equipped with a GPS device, which runs in parallel with the vehicle installed with the PEMS. In the field test, both vehicles drive eight cycles around the designed route, with four cycles following the existing coordinated signal timing and four cycles driving in a manner that makes intentional random stops in front of green lights. After a careful data review, a total of 5,089 PEMS data and 6,092 GPS data are recorded. Based on the manually logged time of each testing vehicle's exact start and end times of each cycle and data characteristics, the PEMS and GPS data collected during each cycle are separated from the whole dataset, and then the amount of CO_2 emissions produced during each driving cycle is estimated using the VSP-based GHG emission modeling approach.

Figure 9 displays a comparison of the total CO_2 emissions generated by the testing vehicle under two testing scenarios. When driving under the emulated non-coordinated signal timing, a total of 8472.87 grams CO_2 emissions are produced; while when driving under the existing coordinated signal timing, a total of 5446.23 grams CO_2 emissions are produced over the same covered distance. Therefore, the total CO_2 emissions generated under the non-coordinated signal timing is about 56 percent higher than those generated under the existing coordinated signal timing.

The total CO_2 emissions generated by hour under the two testing scenarios are also computed. During 3:00 P.M. to 4:00 P.M., the total CO_2 emissions generated by the two testing vehicles are 2617.28 grams per four cycle distance; while that increases to 2828.95 grams per four cycle distance during 4:00 P.M. to 5:00 P.M. One of the reasons that caused the difference in the amount of CO_2 emissions on an hour basis is that with the approaching to rush hour, the increase of traffic flow may compromise the effectiveness of the signal coordination in terms of its influence on the mobile source GHG emission control. The amount of CO_2 emissions generated during each driving cycle under the emulated non-coordinated signal timing are mainly subject to the number of random stops made by the driver, therefore, the total CO_2 emissions generated by hour under this scenario are not comparable.

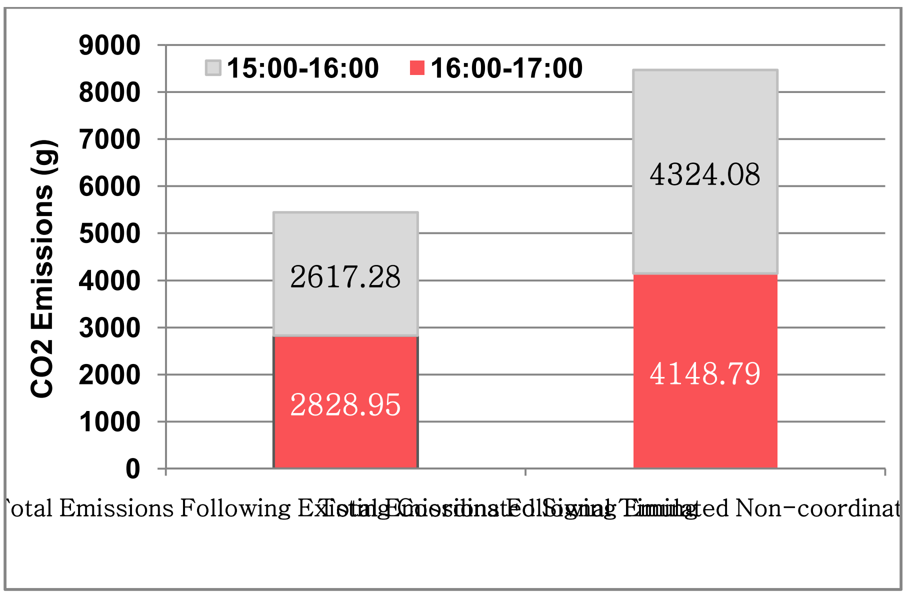


Figure 9 Comparison of CO_2 Emissions Following Existing Coordinated Signal Timing and Emulated Non-Coordinated Signal Timing

Figure 10 displays the comparison of CO_2 emissions generated during each driving cycle. It manifests that when following the existing signal coordination, the average CO_2 emissions produced by the testing vehicle are approximately 680 grams per cycle distance; while that increased to approximately 1000 grams per cycle distance when following the emulated non-coordinated signal timing. Therefore, the existing coordinated signal timing helps reduce about 32 percent of CO_2 emissions per cycle distance comparing with that produced by the emulated non-coordinated signal timing. It is also observed from Figure 10 that Cycle 2 experienced the most significant emission reduction, which is about 50 percent.   Even though Cycle 3 experienced the least amount of emission reduction, the emission reduction rate still reaches about 20percent.

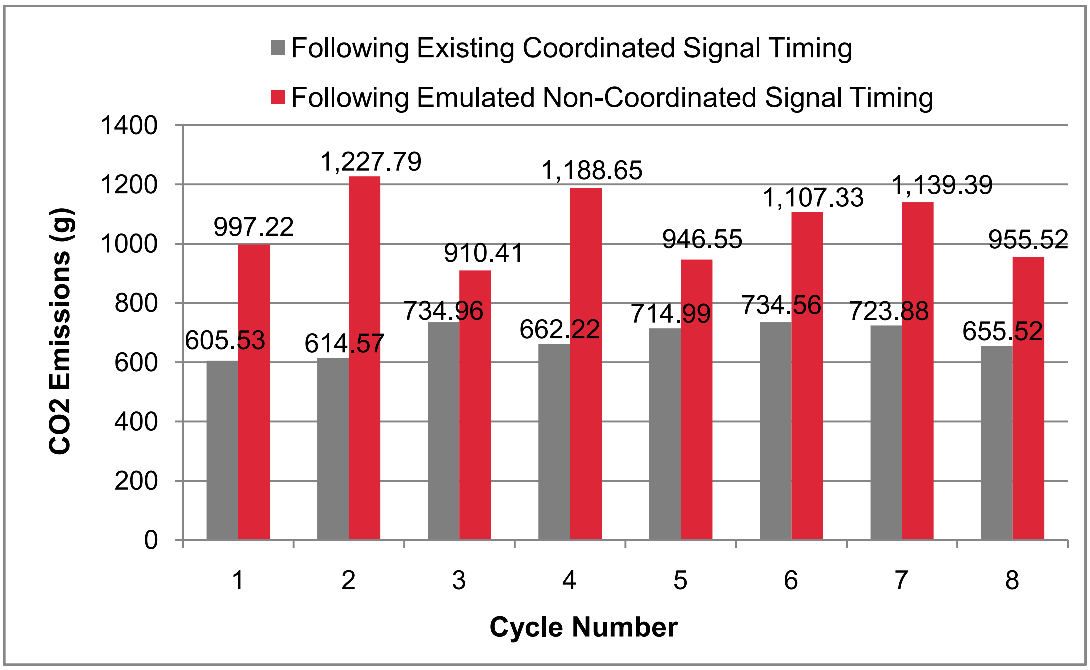
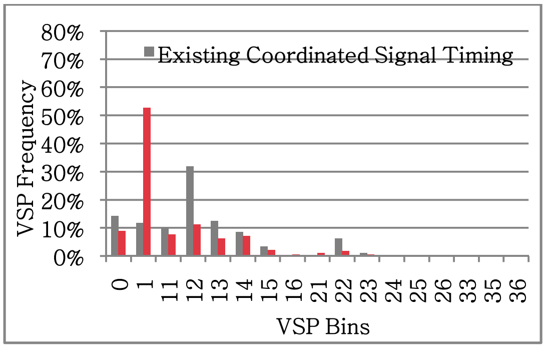


Figure 10 Comparison of CO_2 Emissions Following Existing Coordinated Signal Timing and Emulated Non-Coordinated Signal Timing by Cycle

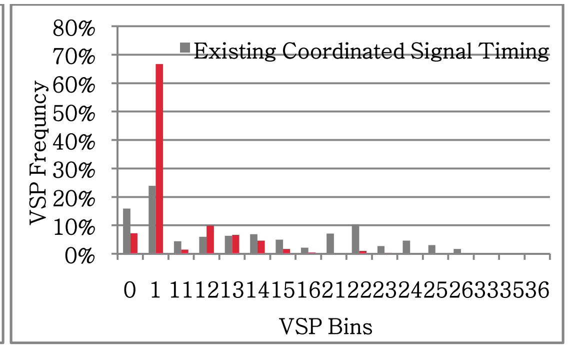
Figure 11 shows the comparison of VSP distributions based on the data collected under the two testing scenarios cycle by cycle. As we know, a traffic signal's level of coordination influences a vehicle's emissions mainly by regulating its stops at intersections and the duration of idling; therefore, the number of data falling into Bin 1 (stands for the operating mode of idling) is an important indicator to determine how well the vehicle follows the coordinated signal timing. Figure 11 shows that in Cycle 1, there is the least percentage of data points falling into Bin 1 when following the existing signal coordination. It is also found that in Cycle 2, Bin 1 contains the highest percentage of data points when following the emulated non-coordinated signal timing.

This result is consistent with the results shown in Figure 10, which demonstrates that during the testing periods, the trip in Cycle 1 following the existing signal coordination generates the least CO_2 mass emissions, and the trip in Cycle 2 following the emulated non-coordinated signal timing generates the highest CO_2 mass emissions.

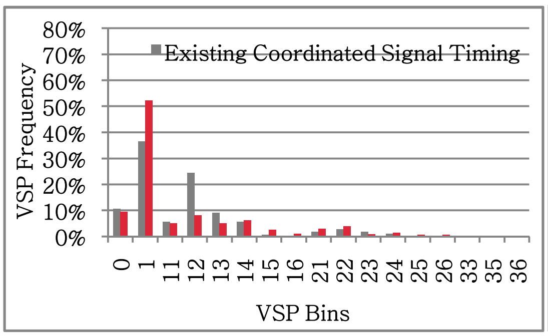
Figure 11 also shows that besides Bin 1, Bin 0 (representing the operating mode of deceleration/breaking) and Bin 12 (representing the operating mode of cruise or acceleration with speed less than 25 mph and $0 \leq VSP \leq 3$) are also important indicators of the vehicle's CO_2 emissions in this study, because Bin 0 and Bin 12 are the bin types that contain a high percentage of data points next to Bin 1.



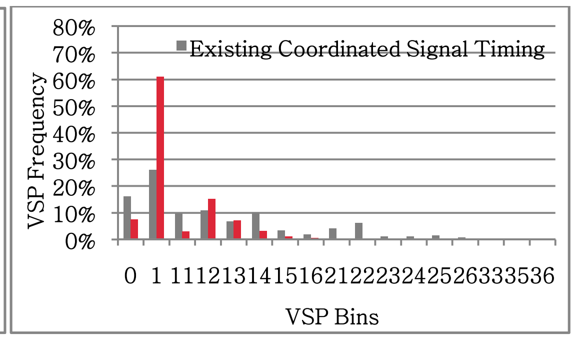
Cycle 1



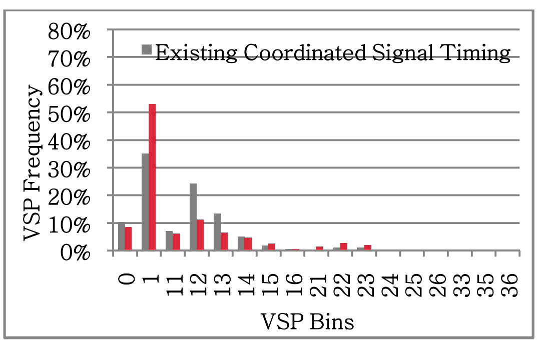
Cycle 2



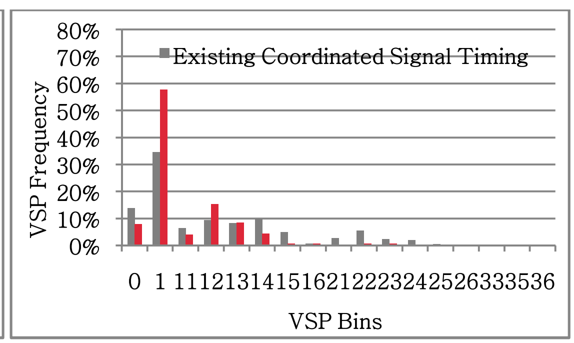
Cycle 3



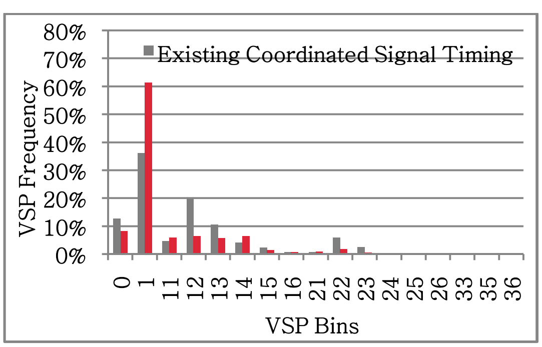
Cycle 4



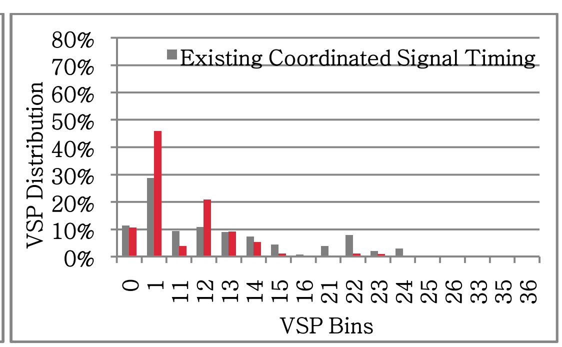
Cycle 5



Cycle 6



Cycle 7



Cycle 8

Figure 11 Comparison of VSP Distributions in Each Cycle

4.4 Evaluation and Analysis of Electronic Toll Collection Scenario

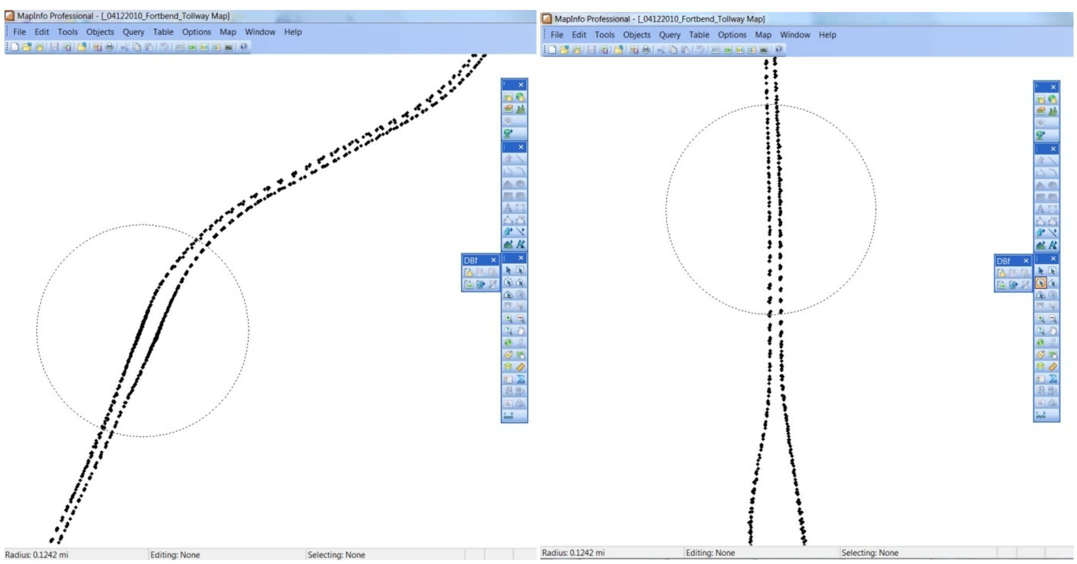
The data utilized for the evaluation of ETC are collected by a light-duty gasoline vehicle between 3:00 P.M. to 4.40 P.M. on April 12, 2010, on a toll road segment along Fort Bend Parkway in Houston. Table 6 shows the basic information about the testing vehicle. As the selected ETC and MTC stations are located on the same freeway segment, the testing vehicle's CO_2 emissions around these two types of toll stations can be directly collected by the PEMS unit within the same driving cycle. After the data screening and pre-processing, a total of 5,989 valid data are recorded for this analysis.

Table 6 Information about the Testing Vehicle for Evaluation on ETC

Make and Model	Ford Taurus
Engine Displacement	3.0 L
Year	2002
Age	8
Mileage	126,000
Fuel Type	Gasoline-petrol
Transmission	4-speed automatic
Horsepower	116kw @ 4900 RPM
Weight	3335.6 lbs
Length	197.6 in

One of critical steps in comparing the amount of CO_2 emissions produced by the testing vehicle around the ETC station and the MTC station is locating the corresponding data collected around the two target places. Based on the experience of toll road driving, it is found that usually a vehicle starts to decelerate at a distance about 200 meters away from the payment site when the vehicle is approaching an MTC station; similarly, when the vehicle is done with the payment and starts to resume the trip, it returns to a comparatively steady speed after 200 meters. Therefore, a length of 200 meters is determined as the threshold to control the length of the roadway segments that fall into the scope of this analysis. In addition, the maximum queue length observed at the MTC station in this study is three vehicles. This length of the queue will not make a big difference on the driving behavior of incoming vehicles 200 meters away from the payment site.

The task of locating the responsive data is accomplished by the geographic information system (GIS) software MapInfo Professional 10.0. MapInfo Professional is powerful Microsoft Windows-based mapping software designed to easily visualize the relationship between data and geography. In order to retrieve the data that are collected 200 meters around the two target toll stations, we first imported the X Y coordinates recorded by PEMS into the software to show the spatial relationship between the vehicle's emissions and its geographic location. Because when the testing vehicle passes through the MTC station, it has to experience a process of deceleration-stop-and-acceleration, which results in a more dense data trace, the area around the MTC station can be directly identified according to data characteristics. The geographic location of the ETC station can be determined by matching its X-Y coordinates displayed in Google Map and recorded by PEMS. Draw a circle of radius 200 meters (about 0.124 miles) around the target toll stations and then the emission data collected within the included areas can be selected. Figure 12 shows the procedure of the data selection.



Selection of Data around MTC

Selection of Data around ETC

Figure 12 Procedure of Data Selection around MTC Station and ETC Station

After the data selection, the numbers of data collected 200 meters around the MTC station and the ETC station are 814 and 168 respectively. The testing vehicle drives five cycles around the designed route and passes each type of toll stations two times per cycle, therefore, 10 sets of emission data are collected around each type of toll stations. Figure 13 shows the comparison of total CO_2 mass emissions produced within 200 meters around the two stations. It illustrates that the total CO_2 emissions produced by the vehicle using the ETC station are only 30 percent of those produced around the MTC station. Figure 14 displays CO_2 emissions produced each time the vehicle passes through each of the selected toll stations. It is observed that with the implementation of ETC, emission reduction rates for each individual passing range from 50 percent to 80 percent comparing to using the MTC station.

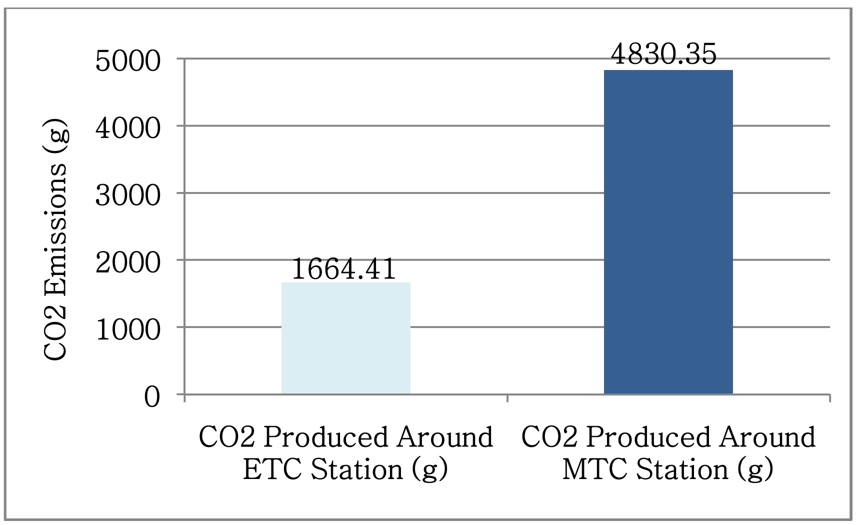


Figure 13 Comparison of Total CO_2 Emissions Produced around ETC Station and MTC Station

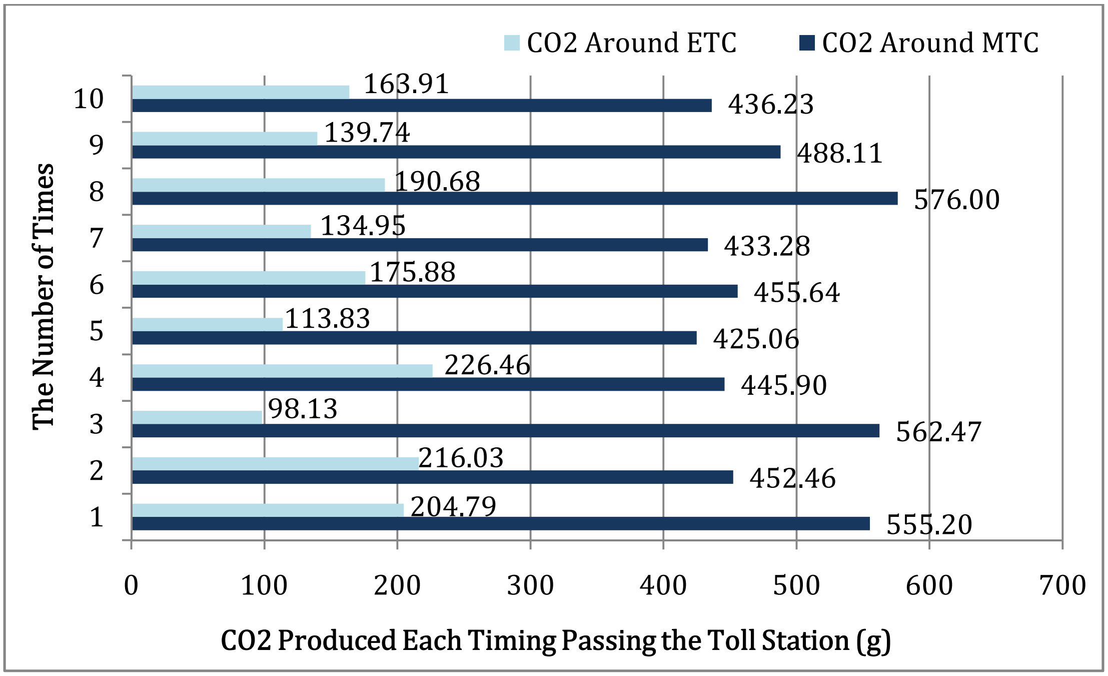


Figure 14 Comaprison of CO_2 Emissions Each Time the Vehicle Passes ETC Station and MTC Station

It is worth mentioning that during the data collection for this analysis, the testing vehicle did not spend a long time waiting in the queue and testers who participated in the data collection were well prepared. In the real-world application, it is possible that drivers may stop longer at the toll station when paying manually in order to know the correct charges, proper paying methods, and look for exact coins or cash. All of these actions may result in even higher CO_2 emissions around the MTC station.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary of the Study

This research is motivated by the intention to reduce mobile source GHG emissions from the perspective of transportation planning and traffic management. This report first introduced the background of this research, including key factors that affect mobile source GHG emissions and uncertainties associated with the mobile source GHG emission estimation. Then, state-of-the-art mobile source GHG emission reduction methods, state-of-the-practice mobile source GHG emission estimation, and limitations that exist in the current study are presented. A comprehensive review on major GHG emission measurement methods, state-of-the-art mobile source GHG emission models, and current studies on the air quality benefit assessment of traffic management strategies is also conducted to gain in-depth knowledge about studies on traffic management related GHG emission control.

HOV lane, traffic signal coordination plan, and ETC are selected as the target traffic management strategies for this study. Data collection scenarios that are able to reflect real-world traffic conditions with versus without the implementation of the selected traffic management strategies are designed and implemented for the purpose of comparison. In the evaluation study, a PEMS unit is used to collect second-by-second real-world emission data and a VSP-based mobile source GHG emission modeling approach is developed as the basis for emission estimations. The main contribution of this research is that it proposed a new traffic management assessment methodology that combines field-testing approach with modeling approach, which is able to reflect a vehicle's real-world emissions, and is easy and convenient to implement.

5.2 Conclusions

In light of discussions and the analysis, this study draws the following conclusions:

1. PEMS represents advanced emission data collection technology. Its ability of collecting a vehicle's second-by-second emission and activity data during its regular operations provides significant advantages over all the traditional emission measurement methods. It can be applied not only in transportation related air quality modeling and analysis, but also in the assessment of traffic management strategies.

2. The proposed emission estimation methodology is a combination of the advantages of the field testing approach and the latest modeling approach. The experimental design of the field testing scenarios provides a pilot study on the impact of a specific traffic management strategy on mobile source GHG emissions using data collected in the real-world traffic network. The VSP-based emission modeling approach provides a credible basis for emission estimation. VSP includes various information of the vehicle's operating mode characterization and explains the variability of fuel use and tailpipe emissions during the vehicle's real-world operating. In this study, the definition of VSP bins embedded in MOVES is used in the binning process in the model development. The validation results indicate that the accurate rate of the proposed modeling approach is about 90percent.

3. HOV lane, well-coordinated signal timing, and ETC are all effective measures to reduce mobile source GHG emissions; however, the level of effectiveness is different for different strategies.

4. The results from HOV lane analysis illustrates that the testing vehicle produces less mass CO_2 emissions per mile by using HOV lane during peak periods. Without the consideration of the effect of HOV lane on vehicle miles traveled, the emission reduction rate on the first testing day is 3.56 percent, and due to an increased traffic demand on the corresponding MF lane on the second testing day, the emission reduction rate by using HOV lane increased to 10.42 percent.

5. Traffic signal coordination impacts a vehicle's CO_2 emissions by regulating its stop-and-go conditions. Based on the comparison of CO_2 emissions generated by the testing vehicle under the existing coordinated signal timing and those generated by the emulated non-

coordinated signal timing, it is found that the non-coordinated signal timing designed in this study leads to about 56 percent increase in CO_2 emissions. In addition, the total CO_2 emissions generated by the testing vehicle on an hourly basis under the existing coordinated signal timing are also compared. The result indicates that the increase of traffic flow may compromise the effectiveness of signal coordination in terms of their influence on mobile source GHG emission controls.

6. Results from the ETC analysis shows that the total CO_2 emissions produced by the vehicle around the ETC station are only 30 percent of those produced around the corresponding MTC station; therefore ETC is a very effective traffic management strategy for reducing mobile source GHG emissions.

5.3 Recommendations

In order to fulfill a more comprehensive analysis about the relationship between traffic management strategies and mobile source GHG emissions, the following recommendations are made for future study in this filed.

1. Improve the VSP-based emission modeling approach by increasing the size of the database used for the model development and develop a finer VSP binning method. The accuracy of the VSP-based emission modeling approach is the basis for the assessment of traffic management strategies in this study. Therefore, it is recommended that more PEMS data be collected to provide a better foundation for the development of the GHG emission modeling approach, and a VSP binning method that is able to better estimate a vehicle's CO_2 emissions in the study area be developed.
2. Evaluate the impact of traffic management strategies on mobile source GHG emissions with the use of different vehicle types. The evaluation of HOV lane, signal coordination plan, and ETC performed in this study provides an exemplary application of the proposed GHG emission modeling approach. The results are based on case-specific scenarios and the particular testing vehicle used in this analysis. Therefore, it is recommended that the applicability of the conclusions drawn from these case studies be assessed for other vehicles.

3. Incorporate cost-benefit analysis into the evaluation of traffic management strategies. Even though the result analysis from this study shows that ETC is the most effective traffic management strategy in terms of mobile source GHG emission control, it is recommended that construction cost, operation and maintenance cost, and comprehensive air quality benefits be considered into the evaluation of the effectiveness of a specific traffic management strategy.

4. Evaluate the impact of traffic management strategies on regional GHG emission reduction. For HOV lane scenario, it is recommended that the impact of HOV lane on vehicle miles traveled be considered in mobile source emission reduction analysis. It is also recommended that the regional air quality benefits for scenarios with versus without the construction of HOV lanes be evaluated. For signal coordination scenario, it is recommended that how different signal coordination plans influence mobile source GHG emissions at regional level be analyzed. For ETC scenario, it is recommended that queue phenomenon be incorporated in future studies about the impact of ETC on mobile source GHG emission control.

APPENDIX

APPENDIX A: ACRONYMS AND ABBREVIATIONS

ACC	Adaptive Cruise Control
ATE	Advanced Travel Center Electrification
CATI	Clean Air Technologies International, Inc.
CARB	California Air Resource Board
CH_4	Methane
CLIP	Climate Leadership in Parks
CMEM	Comprehensive Modal Emissions Model
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOT	Department of Transportation
ECU	Engine Control Unit
EIA	Energy Information Administration
EMFAC	Emission Factors Model
EPA	Environmental Protection Agency
ETC	Electronic Toll Collection
ETV	Environmental Technology Verification
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positing System
GREET	The Greenhouses, Regulated Emissions, and Energy Use in

	Transportation
GWP	Global Warming Potential
HC	Hydrocarbons
HDVs	Heavy Duty Vehicles
HFCs	Hydrofluorocarbons
HOV	High Occupancy Vehicle
HVAC	Heating, Ventilation, and Cooling Systems
I-45N	IH-45 North
I/M	Inspection and Maintenance
IR	Infrared
Kph	Kilometers per hour
Kw/t	Kilowatt/Metric Ton
LDVs	Light Duty Vehicles
LEM	Lifecycle Emissions Model
MOVES	Motor Vehicle Emission Simulator
MPOs	Metropolitan Planning Organizations
N_2O	Nitrous Oxide
NO_X	Nitrogen Oxide
NCDC	National Clean Diesel Campaign
NEI	National Emissions Inventory
NEMS	National Energy Modeling System
NMIM	National Mobile Inventory Model
MF	Mixed-Flow

MPH	Mile Per Hour
MTC	Manual Toll Collection
Pb	Lead
PEMS	Portable Emission Measurement Systems
PM	Particulate Matter
RES	Remote Emission Sensing
RPM	Resolution per Minute
SAGE	Systems for the Analysis of Global Energy Markets
SIT	State Inventory Tool
SOX	Sulfur Oxides
TEM	Transportation Energy Model
UV	Ultraviolet
VMT	Vehicle Miles Traveled
VSP	Vehicle Specific Power
WEPS	World Energy Protection System

APPENDIX B: EMISSION DATABASE STRUCTURE AND EXPLANATION

Fields	Explanation
DATE	Test date(mm/dd/yyyy)
TIME	Test time (hh:mm:ss)
Bag_No.	The number given to each bag
FILE	File name
RPM	Revolutions Per Minute
IAT	Intake Air Temperature (degrees Celsius)
MAP	Manifold Air Pressure (kPa)
GASOURCE	Source of gas analyzer
CO_2	CO_2 concentration (%)
CO	CO concentration (%)
HC	HC concentration (ppm)
O_2	O_2 concentration (%)
NO_X	NO_X concentration (ppm)
PM	Particulate Matter concentration (mg/m3)
FlowIn	Mass of intake air (g/s)
FlowExh	Mass of exhausts (g/s)
CO_2	Carbon dioxide rate (g/s)
CO	Carbon monoxide rate (mg/s)
HC	Hydrocarbon rate (mg/s)

NO_X	Nitrous oxide rate (mg/s)
FuelConsum	Fuel consumption (g/s)
PM	Particulate Matter rate (mg/s)
UTC_Time	Coordinated Universal Time (hh:mm:ss)
Satellites	The number of satellites the signal receives from
LAT	Latitude [ddd] [mm.ssss]
LONG	Longitude [ddd] [mm.ssss]
ALT	Altitude (meter)
Speed	Speed (km/h)
ACCEL	Acceleration ($m \cdot s^{-2}$)
Bearing	Direction (degree)
AmbT_F	Ambient Temperature (degrees Fahrenheit)
AmbP_kPa	Ambient Pressure (kPa)
AmbRH_%	Ambient Relative Humidity (%)

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